CALIFORNIA
ENERGY
COMMISSION

Sagging Line Mitigator Final Report

CONSULTANT REPORT

DECEMBER 2002
P500-02-074F

Gray Davis, *Governor*

CALIFORNIA ENERGY COMMISSION

Prepared By:

Manuchehr Shirmohamadi, Ph.D.
Project Manager

Material Integrity Solutions, Inc.
3254 Adeline St. Suite 200
Berkeley, CA 94703

Contract No. 500-98-042

Prepared For:

David Chambers,
Contract Manager

Laurie ten Hope,
Program Area Lead

Terry Surles,
PIER Program Manager

Steve Larson,
Executive Director

Legal Notice

Acknowledgments

The Sagging Line Mitigator (SLiM) project succeeded due to the hard-working efforts of the project team. Key contributors include:

David Kopperdahl (MIS)

Duc Hai Nguyen (IREQ)

Shawn Bratt (MIS)

Dariush Shirmohamadi (SPEC)

Kiavash Faraji (MIS)

Doron Fishman (MIS)

Keith Leong (MIS)

Andy Reilman (MIS)

John Ridgely (MIS)

Kushy Sachdeva (MIS)

Mohsen Arbabi (MIS)

Dan Kaufman (PG&E)

Material Integrity Solutions, Inc. would like to thank Adam Bell (Patent Attorney), Eric Worrell (Consultant), Ed Beardsworth (Utility Federal Technology Opportunities), and Vito Longo (Consultant) for their contributions toward the SLiM project. Support and contributions from Baj Agrawal (APS), Ali Nourai (AEP), Gouri Bhuyan (PowerTech), Jim Duxbury (BCH), Ram Adapa (EPRI), and Richard Lordan (EPRI) are also acknowledged and appreciated.

Finally, Material Integrity Solutions, Inc. would like to extend its deepest appreciation to the California Energy Commission—specifically to Contract Managers David Chambers and Jon Edwards—for their vision and support of this project.

Contents

List of Figures

List of Tables

Preface

The Public Interest Energy Research (PIER) program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission, annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial / Agricultural / Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration

What follows is the final report for the Sagging Line Mitigator Project (#500-98-042), conducted by Material Integrity Solutions, Inc. The report is entitled *Sagging Line Mitigator Final Report*. This project contributes to the Energy Systems Integration program area.

For more information on the PIER program, please visit the Commission's web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

Background

The current capacity (ampacity) of overhead transmission lines is generally limited by system stability concerns, temperature limit of the conductor material, and thermal sag of the conductor. The latter is by far the most common limiting factor for line ampacity. Heating of overhead conductors by electrical current and high ambient temperatures causes thermal expansion in the line, which increases the effective conductor length and sag. Safety and legal concerns require conductors to maintain specified clearances from the ground and other objects such as roadways and waterways, structures, trees, and other transmission and distribution equipment. Such clearance requirements on only one or a few spans often limit the amount of current that a utility can transport over an entire transmission line. In many cases, clearance requirements are not met, and the span must be repaired or replaced. Current options for resolving sag problems can be costly; the options range from raising towers on either side of a sagging span to reconductoring the line.

The Sagging Line Mitigator (SLiM) device combats excess conductor sag in overhead transmission lines by reducing effective conductor length. It offers an efficient alternative to standard industry approaches at a comparably lower cost. More importantly, use of the SLiM device allows a transmission line to be up-rated, leading to a more efficient use of the existing power grid. As a result, there would be fewer brownouts and blackouts, as well as increased revenues for utilities at a lower cost per kilowatt-hour to the consumer.

Objectives

The objective of the SLiM project was to create a simple, affordable, compact device that can be easily installed on a span to resolve sag problems or to permit up-rating of a transmission line. The guiding design principle was that the SLiM device should be passive and act by reducing effective line length under the same conditions that causes the line to sag. That is, the same temperature change that leads to thermal expansion and sag in transmission line conductor activates the motion of the SLiM device. Upon heating, the device retracts and shortens the effective conductor length. Upon cooling, the device lengthens and releases tension on the conductor.

Methods

To gage the magnitude of line sag problems in the utility industry as well as market demand for a solution such as the SLiM device, the investigators sent market surveys to 33 organizations, including utilities, research laboratories, and regulatory agencies. In general, most organizations acknowledged a sag issue and indicated interest in our solution. Results of the survey also concluded that the majority of sag problems occurs on 115–230kV lines under high load on hot days, and that the excess sag is typically less than 5'.

Based on the survey results, the SLiM design was targeted for 230kV class transmission lines. We selected the 795kcmil ACSR (aluminum conductor steel reinforced) conductor (26x7 Drake or 54x7 Condor) as the target conductor because it was the most common 230kV conductor used in the Western Electricity Coordinating Council (WECC) region. However, other conductors were also used in the study presented here. The target range of motion of the SLiM device was established at ~6" when the conductor heats to 212°F. With this range of motion, one device would be capable of mitigating over 50" on a 500' span of Drake. The breaking load of the SLiM device was set at 35,000 lbs., or 110% of the breaking load of Drake conductor (31,500 lbs.).

The SLiM device uses a mechanical lever arm to magnify the length change of its actuator, thereby shortening or elongating the effective length of conductor on a span. The actuator consists of shape memory alloy wires held parallel to one another by swaging the ends of the wires into custom closed swage sockets. The shape memory wires shorten when heated, and are lengthened by the conductor tension when cooled. A pipe, machined to proper form, serves as the body of the device. The pipe acts as the fulcrum for the lever magnification, and reduces the corona of the device by enclosing most of the components in a round cross-section. The lever arm provides a 5.5:1 magnification of the actuator length change, and gives the device a stable triangular form. Installed in series with the conductor, the SLiM device carries the full line current, splitting the current between the actuator and the body of the device. Flexible connectors carry current between the transmission line and the SLiM device, and between the body and the actuator.

Materials for the SLiM components were selected based on a number of criteria, including mechanical strength, electrical characteristics, wear rate, corrosion resistance, and cost. During the design process, finite element software was used to analyze for stress conditions in device components and the electric field density on critical cross-sections through the device. Factors of safety on stress were maintained to at least a factor of two, and corona was kept below a field density of 21kV/cm.

Analyses using the industry standard Electro-Magnetic Transients Program indicated that the SLiM device produces negligible impact on the electrical transient behavior of the transmission line. In addition, a frequency analysis showed that the device had a negligible effect on the natural frequencies of the transmission line in the vertical and lateral direction. In the longitudinal direction, the SLiM device reduced the dominant natural frequencies by an amount similar to the effect Richardson type aerodynamic drag dampers used to control galloping.

Results

Design and development of the full-scale SLiM device involved laboratory tests on several levels:

- Components of the device, including shape memory alloy used in the actuator and the swage fittings, were tested to determine their behavior and strengths.
- A small-scale prototype was tested to demonstrate the feasibility of the SLiM concept. After successful completion of the small-scale prototype, work began on the full-scale device.
- Functionality testing was performed in the laboratory on a full-scale prototype to verify proper operation and to determine its range of motion.
- Functionality testing was then performed on a live transmission line to demonstrate its sag reduction capabilities under real-world conditions. On a 500' span of 795kcmil 54/7 ACSR (condor) conductor, the SLiM device reduced sag by 44" relative to a control span when heated from ambient to 212°F.

- A reliability test was performed to gage fatigue life; corrosion resistance; change in resistance, if any, at the electrical connections; and overall integrity of the device. Fatigue test on the shape memory alloy used in the SLiM actuator indicate that the device would have a safe service life of over 30 years. Corrosion tests demonstrated that the device will have significant resistance to corrosion in most outdoor environments including those with acid rain and ocean spray. A 525 cycle test showed no significant change in the resistance across electrical connections, but did identify two joints in the device that would require slight modification to maintain a high integrity and high factor of safety during service. These modifications have already been employed in the production version of the device.

Two other products were developed as a result of the SLiM project:

- A sag mitigation device called the SmartConductor
- A complex terrain modeler, which is a procedure for determining when and where to install sag mitigating devices on a transmission line

In its current configuration, the SmartConductor is a 6' length of conductor that shortens when heated due to its shape memory alloy core. Constructed using standard industry connectors, the device is *assembled* rather than *fabricated*. With about 30% of the range of motion of the SLiM device, the SmartConductor is a lower-cost alternative to the SLiM device for applications that require less sag mitigation. During the full-scale functionality tests, the SmartConductor reduced sag by 10" relative to a control span when heated from ambient to 212°F.

Optimizing the use of SLiM devices in actual applications requires a tool for determining where in a transmission line the devices will be most effective. This is especially true for cases where insulator swing allows for tensions to equalize and hence reduce the effect of a single SLiM device. Therefore, to determine the optimal locations and number of SLiM devices required to resolve a sag problem, we developed a simulation technique (Complex Terrain Modeler using finite element software) that considers the entire transmission line section.

Conclusions

This project achieved its goals by creating simple, affordable, compact, and passive control devices (SLiM and SmartConductor) that can be easily installed on a span to resolve sag problems or to permit up-rating of the line. The resulting designs are the first of their kind to effectively reduce conductor sag in a live-line demonstration.

SLiM and SmartConductor devices can eliminate the thermal sag problem faced by many utilities in the world. Since the production and installation of these devices are simple, it will become a very attractive alternative to other sag mitigation techniques. Based on a simple market analysis, considering conservative market size and market penetrations, we estimate the demand for this product will be in excess of 30,000 units in North America alone.

Recommendations

Before the SLiM device can be adopted by the utility industry, some additional tasks are needed. These include development of a production prototype to optimize the cost of making the devices and a utility-wide demonstration of the device on actual transmission lines. Furthermore, we feel a relationship with an existing major manufacturer, supplier, and/or distributor in this industry will benefit the production and introduction of this device. Other plans include publishing articles and making presentations at various forums to increase the awareness about this product.

Work on the design of the production model has already started and we are exploring partnerships for finalizing manufacturing processes, distribution, and sale / support of these devices. Also, in cooperation with Electric Power Research Institute (EPRI), a tailored collaboration project is being developed where production versions of the device will be installed on actual transmission lines and their performance monitored for approximately one year. We are also preparing a number of presentations about this device to be given in IEEE and other forums.

With a production plan and the proposed large-scale demonstration project by the EPRI in the works, we are confident that the SLiM and SmartConductor devices will have a strong and promising future in the electric transmission industry.

Benefits to California

The Slim and SmartConductor devices have the potential to offer the following benefits to California.

- Improved reliability and quality of California's electricity system by reducing the risk of brownouts (the curtailment of electric deliveries due to line constraints) and power supply interruptions;
- Improved safety of California's electricity by significantly reducing the risk of electrocution and fires caused by sagging transmission and distribution lines; and
- Reduced environmental and public health risks / costs of California's electricity system by avoiding the need to build additional transmission towers.

Abstract

This research and development project was initiated to develop and demonstrate a new family of line hardware, based on an existing invention, to mitigate thermal sag problems of transmission lines. The goal of the Sagging Line Mitigator (SLiM) project was to create a simple, affordable, compact device that can be easily installed on a span to resolve sag problems or to permit up-rating of a transmission line. Through market research and several design and testing iterations, this project achieved its goal and developed and successfully demonstrated a family of products that meets that need.

Significant project outcomes included:

- Market surveys demonstrated a widespread recognition of excess sag problems within the electric transmission industry and identified the criteria for the SLiM device.
- Employing feedback from the utility industry and a number of design iterations, the investigators explored a wide variety of devices and configurations for the SLiM device before finally arriving at two robust sag mitigation designs—SLiM and SmartConductor. This process employed specialized analytical tools, literature searches, new connection techniques, customized load frames and data acquisition systems, and laboratory testing, backed up by close correspondence with various manufacturers and suppliers.
- Full-scale tests successfully demonstrated the functionality of the SLiM and SmartConductor devices when installed on a live transmission line.
- A simulation technique (complex terrain modeler) was also developed to optimize the number and location of these devices on a given section of transmission line.

The final challenge for this project is to develop and institute production devices and a marketing effort to introduce the device to the electric utility industry.

1.0 Introduction

1.1. Background

Over 31,000 miles of transmission line comprise the electricity transmission grid in California [1], delivering 254 GWh of electricity to commercial and residential customers in 2001 [2]. Given the statewide weighted average electricity rate of 13.25 cents / kWh [3], electricity transmission represents a $33.6 billion per year industry in California alone. As little as a 1% increase in the efficiency of the grid translates to increased savings of $920,000 per day.

The current capacity (ampacity) of overhead transmission lines is generally limited by system stability concerns, temperature limit of the conductor material, and thermal sag of the conductor. The latter is by far the most common limiting factor for line ampacity. Heating of overhead conductors due to electrical current and high ambient temperatures causes thermal expansion in the line and increased sag. Safety and legal concerns require conductors to maintain specified clearances from the ground and other objects such as roadways and waterways, structures, trees, and other transmission and distribution equipment. Such clearance requirements on only one or a few spans often limit the amount of current that a utility can transport over an entire transmission line. In many cases, clearance requirements are not met, and the span must be repaired or replaced. Current options for resolving sag problems include de-rating the line on hot days, raising towers, or reconductoring. These options are usually very costly and in some instances may introduce uncertainties with line operation.

The Sagging Line Mitigator (SLiM) device combats excess conductor sag in overhead transmission lines (Figure 1:). It offers an effective alternative to standard industry approaches at a comparably lower cost. More importantly, use of the SLiM device allows a transmission line to be up-rated, leading to a more efficient use of the existing power grid. As a result, there would be fewer brownouts and blackouts, as well as increased revenues for utilities at a lower cost per kilowatt to the consumer.

Figure 1: Full-scale prototype of the Sagging Line Mitigator.

To gage the magnitude of line sag problems in the utility industry and market demand for a solution such as the SLiM device, the investigators sent market surveys to 33 organizations, including utilities, research laboratories, and regulatory agencies. A discussion of the survey and results from the 18 respondents is in Appendix A. In general, most organizations acknowledged a sag issue and indicated interest in purchasing a device such as SLiM, provided that it was field tested and economically priced. The following list is a summary of findings from the survey:

- A majority of the responding utilities indicated that they have sag problems.
- Sag problems are of most concern on lines with ratings of 115–230kV.
- Sag problems are equally prevalent in urban and rural areas.
- The majority of sag problems occur under high-load conditions on hot days.
- The majority of sag problems are less than 5' of excess sag.
- The most common methods for addressing the sag problem are limiting line load and raising towers.
- Current methods for dealing with sag are effective, but they are not economical.

A survey of the existing power grid (Appendix B) indicated that 230kV lines are the most common conductors used for electric transmission in the Western Electricity Coordinating Council (WECC) Region (Table 1:). As of 1999, 37,534 miles of 230kV transmission line comprised more than 50% of the WECC grid for voltage ratings of 115–500kV. This, along with the fact that these lines are usually “thermally limited” rather than “stability limited” (as for 500+kV lines), led to the selection of a 230kV voltage rating for the initial development of the SLiM device. After the device is successfully demonstrated for this voltage category, it can be easily expanded to other voltage ratings.

Table 1: Total Transmission Lines by Voltage Rating in WECC

Voltage Rating (kV)	Year-end Date	Transmission Type	Type of Support	Structure Mileage	Circuit Mileage
115–168	1999	AC	Aboveground	9,912	13,109
230–287	1999	AC	Aboveground	30,007	37,534
345–360	1994	AC	Aboveground	7,756	8,749
500	1999	AC	Aboveground	13,056	15,268

The SLiM device operates on the principle of reducing the effective conductor length. Excess sag occurs when the effective length of the conductor increases due to thermal expansion. For example, an increase in conductor temperature from 110°F to 212°F on a 1,000' span of Drake conductor leads to 6' of additional sag, but only an 11" increase in the effective length of the conductor on that span. The amount of additional sag considered excessive depends on clearance requirements for that particular span. Assuming that half of the sag was excessive, the SLiM device would need to shorten the effective line length by only 5–6" to resolve the sag problem. If this span limited the load rating of this line, then any additional take-up in the effective conductor length would permit up-rating of the line.

1.2. Project Objectives

The goal of the SLiM project was to create a simple, affordable, compact device that can be easily installed on a span to resolve sag problems or to permit up-rating of a 230kV transmission line.

Since inception of the SLiM concept and award of its patent, the SLiM device has undergone extensive development, design, and testing. The result is a full-scale prototype that has proven itself not only in laboratory testing but also in live line field testing on a transmission line.

1.3. Report Organization

Section 2 discusses the design, operation, and testing of the SLiM device.

Section 3 discusses two other products that were developed as a result of the SLiM project—the SmartConductor and a complex terrain modeler. The SmartConductor is a sag mitigation device that has a smaller range of motion and a lower cost than the SLiM device. The complex terrain modeler software determines how many sag mitigation devices are needed for a problem transmission line section and where the devices should be placed.

Section 4 summarizes the steps taken to produce the SLiM device and highlights important test results.

Section 5 presents the conclusions drawn from the project experience and recommendations for further action.

2.0 Project Approach

2.1. Criteria

Prior to designing the SLiM device, we established a set of design, performance, and cost criteria. A brief summary of these criteria is reported here, and a full listing of all criteria is in Appendix C.

2.1.1. Performance and Design Criteria

The SLiM device was designed to combat the problem of excess sag on a transmission line span. Current industry procedures, such as raising towers or decreasing tower spacing, reduce excess sag by increasing clearances. Excess sag, however, is caused by thermal expansion of the conductor. Any savings in excess sag produced by increasing clearances a matter of feet can be accomplished by shortening the effective conductor length a matter of inches. The guiding design principle was that the SLiM device should act by reducing effective line length. Furthermore, the action of the device should be passively actuated by the same temperature change that produces thermal expansion of the conductor—in other words, no electronic controls.

Because conductor clearances vary from location to location, a nonspecific definition of excess sag was required to establish design criteria. To do this, we investigated sag-tension profiles on six 230kV conductors ranging in diameter and construction (Table 2). The maximum current for each conductor was defined as the current that heats the conductor up to the annealing temperature of the aluminum (212°F) under typical ambient temperatures for California (70°F) with very little wind available to cool the line (2 ft / sec). Typical conductor temperature was then defined as the temperature of the conductor carrying 50% of its maximum current during typical ambient conditions. For the six selected conductors, temperatures ranged from 112–117°F, with a mean of 114°F. Therefore, the working range of the SLiM device was established as 110–212°F; that is, the SLiM device was designed to mitigate the additional sag that occurs between 110°F and 212°F.

Table 2: Maximum Current and Typical Temperature for Various 230kV Conductors

Conductor	Type	kcmil	Stranding	Maximum Current (A) *	Typical Temperature (°F) †
Thrasher	ACSR	2,312	19 x 76	2264	117
Rail	ACSR	954	7 x 45	1259	114
Drake	ACSR	795	7 x 26	1137	113
Marigold	AAC	1,113	61	1340	114
Magnolia	AAC	954	37	1274	114
Rex	AAAC	504	19	783	112

* Current that heats conductor to 212°F with 70°F ambient temperature and 2 ft/sec wind.

† Conductor temperature at 50% maximum current, 70°F ambient temperature, and 2 ft/sec wind.

SLiM acts by shortening the effective length of the conductor. To establish a criteria for the range of motion required by the SLiM device, we determined the effective length change of the conductor due to heating from 110–212°F, given a reference tension of 20% of the breaking load at 40°F (a common industry practice). We determined effective length changes for the six conductors with span lengths of 500' and 1,000' (Table 3). Length changes varied from 5" to 15" on 500' and 1,000' spans, respectively.

If the device were designed to counteract effective length change for the worst case scenario, tensions would be too high on shorter spans or on spans with less of a sag problem. The device was therefore targeted at the low end of the range, with the intention of using multiple devices on a span that required more sag mitigation.

We selected the Drake conductor (795kcmil, 7x26, ACSR) as the target conductor because it was the most common 230kV conductor used in the WECC region (Appendix B). On a 500' and 1,000' span, the effective length of Drake increases by 5" and 11", respectively, when heated from 110°F to 212°F. Therefore, the target range of motion of the SLiM device was established at 5–6". With this range of motion, one device would be capable of mitigating all the additional sag (4'–4") on a 500' span of Drake that occurs when the conductor is heated from 110°F to 212°F, and two devices would take up the additional sag of 6'–4" on a longer span of 1,000'.

Table 3: Sag, Tension, and Elongation of Various 230kV Conductors When Heated

Conductor	Span	Tension †		Sag		Range of Motion ‡
		110°F	212°F	110°F	212°F	110°F to 212°F
	(ft)	(lb)	(lb)	(ft)	(ft)	(in)
Thrasher	500	8949	5983	8.8	13.2	6.2
Thrasher	1000	10449	8680	30.3	36.4	13.1
Rail	500	4101	2672	8.2	12.6	5.8
Rail	1000	4810	3925	28.0	34.3	12.5
Drake	500	4749	2984	7.2	11.5	5.1
Drake	1000	5557	4428	24.6	30.9	11.2
Marigold	500	3158	2214	10.3	14.8	7.1
Marigold	1000	3655	3131	35.8	41.8	14.9
Magnolia	500	2649	1876	10.6	14.9	7.1
Magnolia	1000	3054	2633	36.7	42.6	14.9
Rex	500	1834	1139	8.1	13.0	6.6
Rex	1000	2205	1738	26.8	34.1	14.1

† The design tension in the conductor is set to 20% of the breaking load at 40°F.

‡ Range of motion required of the SLiM devices to eliminate the excess sag that occurs between 110°F and 212°F is equal to the thermal expansion of the conductor between these two temperatures.

Using Drake as the target conductor helped to establish several other design criteria (Table 4). The maximum operating current of 1,200 amps was set just above the current that heats Drake to 212°F when ambient temperature is 70°F and wind speed is 2 ft/sec. A maximum operating tension of 5,000 lbs. was taken as the tension of Drake on a 1,000' span with a conductor temperature of 110°F. The breaking load of the SLiM device was set at 35,000 lb, or 110% of the breaking load of Drake (31,500 lb).

Table 4: Selected Performance and Design Criteria for the SLiM Device

Criteria	Target Value
Voltage Rating	230kV and below
Target Conductor	Any conductors with a breaking load of 31,500 lb or less
Range of Motion	Up to 6"
Amperage	Adjustable
Target Line Tension @ 110°F	~5,000 lbs. (can be adjustable)
Functional Temperatures	110–212°F (conductor temperature)
Mechanical Failure Load	~35,000 lbs.

2.1.2. Cost Targets

For the SLiM device to achieve success in a utility market that is often resistant to change, utilities must perceive it as a more economically viable option than current methods for addressing excess sag problems. Current options include:

- Constructing a new line to replace or reduce load on the existing line.
- Reconductoring with a larger conductor.
- Bundling more conductors on existing towers.
- Adding towers to decrease span length.
- Raising towers to increase clearance.

Table 5 gives a relative look at the advantages and disadvantages of each option. Appendix C contains a more detailed description and an economic analysis of these options.

Table 5: Advantages and disadvantages of various sag mitigation options

	Option#1 New Line	**Option#2** Re-conductor	**Option#3** Bundled-line	**Option#4** Add Tower	**Option #5** Raise Towers	**Option #6** Install SLiM
Approx. Cost ($)	480,000	>144,000	>144,000	>40,000	>25,000	Target
Prob. Of higher cost?	Med.	High	High	High	High	Target-low
Environmental impact	High	Low	Low	High	Low	None
Visual Aggression	High	None	Low	High	High	Low
Live-line work?	Maybe	No	No	No	Maybe	Yes
Applies to all profiles and configurations?	Yes	Maybe	Maybe	Maybe	No	Yes
Failure Risk during installation?	Low	Low	Low	Med.	High	Low
Reliability of option?	High	High	High	Med.	Low	High

For an isolated sag problem, raising towers is most often found to be the least expensive of those options listed. Therefore, for SLiM to be cost-competitive, the installed cost of all devices near a single tower should not exceed the cost of raising towers.

2.2. Design

Since the first patent was awarded in 1997, SLiM has evolved through a number of design iterations (Appendix D). Two installation configurations were initially considered:

- Hung from a tower in place of or in series with an insulator
- Inline with the conductor away from the towers

Conceptual designs included devices with actuators that act in axial compression or axial tension, or by bending or rotating. Designs were considered that magnified the actuator motion through one set of levers (single magnification), two sets of levers (double magnification), or with no magnification at all. Single and multiple actuator designs were considered using either wire or rods of shape memory alloy or other materials.

The final design is a single actuator, single magnification device using shape memory alloy wires that act in tension. The device is installed in series with the transmission line.

2.2.1. Description of Device

The SLiM device uses a mechanical lever arm to magnify the length change of its actuator, thereby shortening or elongating the effective length of conductor on a span (

Figure 2:). The actuator consists of shape memory alloy wires held parallel to one another by swaging the ends of the wires into custom closed swage sockets. A pipe, machined to proper form, serves as the body of the device. The pipe acts as the fulcrum for the lever magnification, and reduces the corona of the device by enclosing most of the components in a round cross-section. The lever arm provides a 5.5:1 magnification of the actuator length change, and gives the device a stable triangular form. Installed in series with the conductor, the SLiM device carries the full line current, splitting the current between the actuator and the body of the device. Flexible connectors carry current between the transmission line and the SLiM device, and between the body and the actuator.

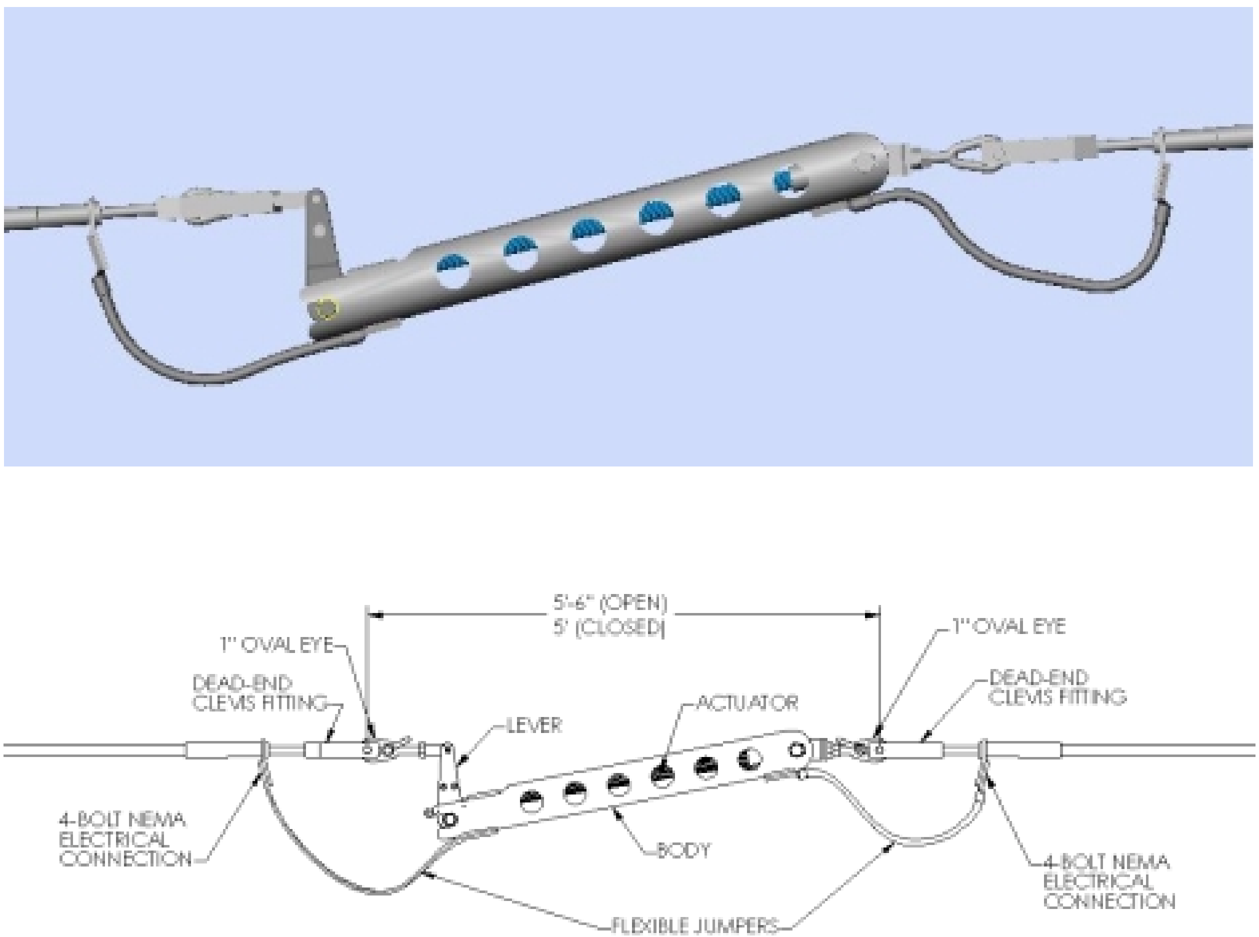

Figure 2: 3-D Rendering (top) and schematic (bottom) of the Sagging Line Mitigator.

2.2.2. Description of Device Components

Actuator—the actuator consists of shape memory alloy wires held parallel to one another by swaging the ends of the wires into custom closed swage sockets (Figure 3:). For the current design, the active length of the actuator (the length of wire exposed between the swage sockets) is approximately 3'. The socket assemblies provide good electrical connections for the current, as well as good mechanical connections to load the actuator. The actuator is loaded in tension by the magnified conductor tension. The actuator shortens as temperatures increase, and lengthens as temperatures decrease. Although most of the current passes through the SLiM body, a fraction of the current passes through the actuator wires, providing the heat required for transformation.

The number of shape memory wires used in the actuator is determined by the conductor tension. The appropriate number of wires is chosen such that the magnified conductor tension produces a nominal stress of ~30ksi in the wires. This stress level provides an effective trade-off between transformation strain, which peaks at around 50ksi, and fatigue life, which decreases as stress increases. At 30ksi, the shape memory alloy has a transformation strain of approximately 3%. A 3' actuator, for example, contracts approximately 1" when heated through its transformation regime.

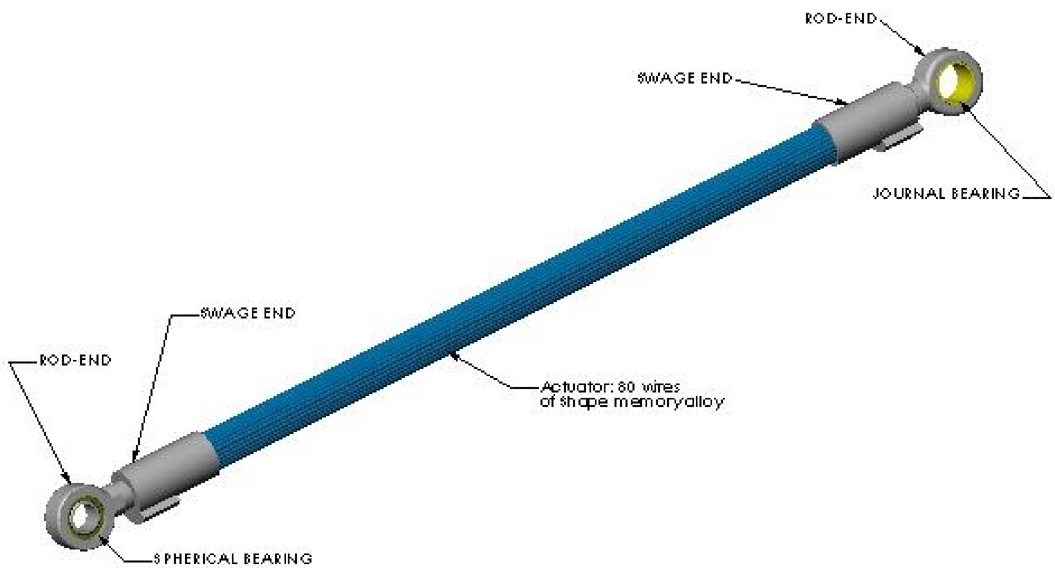

Figure 3: SLiM actuator assembly.

Rod-ends—Threaded rod-ends connect the actuator to the lever on one end via the axle, and to the SLiM body on the other end via the shaft. Threads allow adjustment of the overall actuator length, ensuring an easy fit in the body. Bearings are pressed into the rod-ends to prevent excess wear at the pinned joints.

Body and Fulcrum—The body of the prototype SLiM was machined from a standard 5" diameter 304 stainless steel pipe. The pipe acts as the fulcrum against which the actuator pulls, provides the strength to support the magnified conductor tension, and improves corona behavior by enclosing much of the device. Machined holes near the ends of the body provide pivot points for the joints at either end of the actuator. Larger holes in the side of the body allow wind to pass through the device such that the actuator experiences the same ambient conditions as the transmission line. This is important because the actuator must experience the same fluctuations in temperature due to ambient wind as the transmission line if it is to react to changes in conductor sag at the appropriate time.

Lever Arm—the lever arm provides the magnification (Figure 4:). Although the lever for the prototype SLiM was machined from high strength steel, the production version may use a cast or forged part to reduce cost. The current design uses only one lever arm on one side of the device giving the linkage assembly a stable triangular configuration.

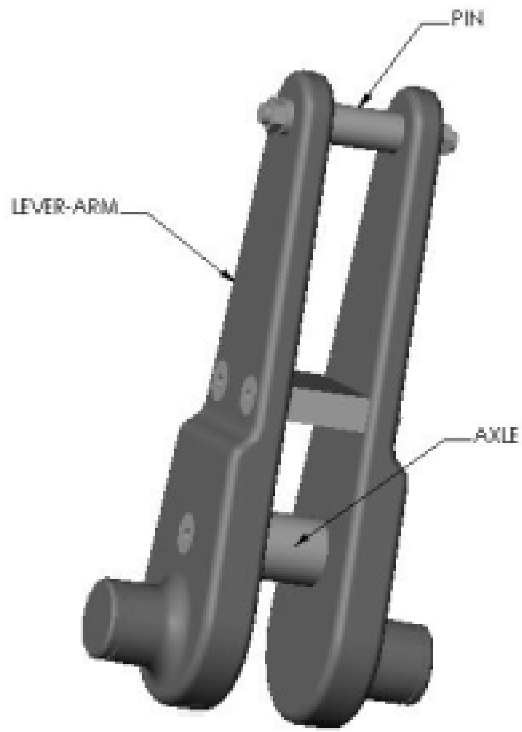

Figure 4: Lever arm assembly.

Safety Link (not pictured)—the safety link is a 5' length of polyester roundsling with a breaking strength greater than 110% of the conductor breaking load. Although the actuator supports the conductor tension most of the time, the safety link supports the conductor tension when conductor temperatures drop below about 100ºF. This is the approximate temperature of 795kcmil, ACSR, Drake conductor on a cold day, 50ºF, with half of the maximum allowable current. The safety link also engages in the event of an overload or mechanical failure of the actuator or a joint in the linkage assembly.

Shafts and Bearings—the axle, shaft, and pin comprising the joints of the linkage assembly are 17-4PH stainless steel ground and polished to provide good bearing surfaces. The post bearings and the bearing on the shaft and pin are steel-backed PTFE / fiberglass composite sleeve bearings. The bearing on the axle is a PTFE composite spherical plane bearing.

Condition Indicator—The condition indicator shows the angle between the lever and the body of the SLiM device. It is visible at a distance using binoculars, and it is used to monitor proper functioning of the device.

2.2.3. Installation Configuration

The SLiM device is installed in series with the transmission line. Either end of the device is equipped with standard oval-eye end fittings. The mating attachment on the conductor is the choice of the utility. The device accepts any industry standard dead-end attachment with a clevis that is compatible with a 1" oval eye. The line attachment should be able to withstand the full line load, conform to industry standards for dead-end connectors and / or full tension splices, and conform to standard installation practices and tools. Options include dead-end compression fittings (Figure 5:), preformed dead ends, and wedge dead ends. (Appendix E for more details.)

Figure 5: Dead-end compression fitting.

2.2.4. Actuator Heating/Current Path

The SLiM actuator shortens when heated and lengthens when cooled because of a solid phase transformation in the actuator wire shape memory material. Heating of the SLiM device, and thus the phase transformation, is accomplished by passing current directly through the actuator (Appendix F). On the lever side of the SLiM device, current is carried from the dead-end connector on the transmission line to the body of the SLiM via a commercially available flexible jumper. This jumper is bolted to both the dead end and the SLiM body using standard NEMA connections.

Although most of the current is passed through the body of the SLiM device, about 30% passes through the actuator via flexible connectors. These connectors span between the SLiM body and the swaged ends of the actuator, placing the actuator electrically in parallel with the SLiM body. The current path is completed by a standard aluminum jumper attached to the SLiM body on one end, and the transmission line dead end on the other. To prevent arcing, all components of the device are maintained at the same electric potential via metal-to-metal contact.

2.2.5. Materials

Selection of SLiM component material was based on a number of criteria, including mechanical strength, electrical characteristics, wear rate, corrosion resistance, and cost.

2.2.5.1. Actuator Material

The actuator material is a shape memory alloy consisting of nickel and titanium (NiTi). The actuator repeatedly expands or contracts when heated and returns to its original length when cooled. The effective reduction in conductor length is approximately equal to the length change of the actuator times the 5.5:1 magnification factor of the lever. Conversely, the reaction forces on the actuator are approximately 5.5 times conductor tensions of up to 5,000 lb. Therefore, the load that the actuator must withstand is up to 30,000 lb. To maximize the length change in the conductor and to minimize the reaction forces on the actuator, the actuator material undergoes a large expansion / contraction in response to temperature change. Its high strength and large inelastic deformation, which is recoverable upon heating, make the NiTi shape memory alloy ideal for this application.

A temperature-deformation diagram (Figure 6:) demonstrates the shape memory effect in NiTi. Table 6 lists the physical, mechanical, and electrical properties of NiTi. At “low” temperatures, the material is martensitic and easily deforms from its original shape. As temperature increases, the NiTi matrix transitions to austenite phase. During the transition, the bulk shape returns to its original form. As the NiTi is cooled, the matrix transitions back to martensite, allowing the bulk shape to be easily deformed again by external forces. By repeating this process, a NiTi actuator can be cycled between two shapes with a high degree of dimensional accuracy.

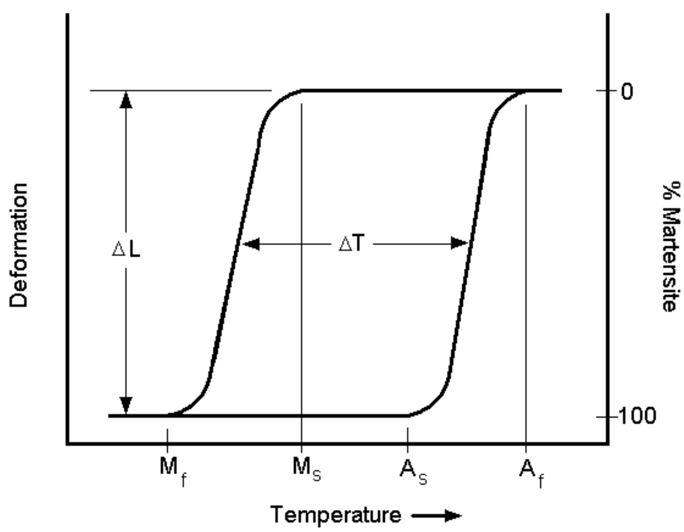

Figure 6: Temperature-deformation diagram for NiTi showing all four transformation temperatures (Mf, Ms, As, Af) and the thermal hysteresis (ΔT).

Table 6: Properties of NiTi Shape Memory Alloy

Property	Austenite	Martensite
Density	6.45 g/cc	6.45 g/cc
Mechanical Properties		
Ultimate Strength, Tensile	123,250 psi	123,250 psi
Yield Strength, Tensile	81,200 psi	14,500 psi
Elongation at break	15.50%	15.50%
Modulus of Elasticity	10,875 ksi	4,060 ksi
Poisson’s Ratio	0.3	0.3
Shear Modulus	4,205 ksi	1,595 ksi
Thermal Properties		
Heat Capacity	0.08 BTU/lb-°F	0.08 Btu/lb-°F
Thermal Conductivity	69 BTU-in/hr-ft^2-°F	69 Btu-in/hr-ft^2-°F
Melting Point	2,264°F	2,264°F
Solidus	2,264°F	2,264°F
Liquidus	2,390°F	2,390°F
Electrical Properties		
Electrical Resistivity	820 nΩ-m	760 nΩ-m
Magnetic Susceptibility	38×10^{-7}	25×10^{-7}

The actuator's swage sockets were fabricated from hot rolled carbon steel. The swage sockets transmit both load and current to the actuator wires, via a swage connection. Therefore, we needed a steel with high strength and high ductility that would not crack during swaging. For production, stainless steels will also be considered.

2.2.5.2. Frame Components

The following issues were considered when selecting frame material:

- The frame supports the transmission line tension during normal operation.
- The frame permits motion that magnifies the expansion of the actuator.
- The frame resists stresses incurred from magnifying the actuator motion.
- The frame provides a means of attaching to the transmission line.
- Because the device is bare and exposed to the atmosphere, the frame material must be resistant to corrosion, including galvanic corrosion between mating metals.
- The material for various components of the frame is compatible with each other as well as with the actuator, bearings, and pins.

Table 7 lists frame components and their materials and material properties.

Table 7: Properties of Steels Used in the SLiM Device

Property	Units	304 Stainless Steel	17-4PH Stainless Steel	AISI-4140 Carbon Steel	AISI-1045 Carbon Steel	AISI-1018 Carbon Steel
Components		Body	Axle, shaft, pin	Rod ends	Lever	Clevis, eye-connector
Material Properties						
Density	lb/in³	0.289	0.282	0.284	0.284	0.284
Brinell Hardness		123	341	277	170	126
Mechanical Properties						
Ultimate Strength, Tensile	ksi	73.2	164	128	74.7	63.8
Yield Strength, Tensile	ksi	31.2	148	99.4	70.3	53.7
Elongation at Break	%	70	17	19.2	10	15
Reduction of Area	%	—	59	60.4	25	40
Modulus of Elasticity	ksi	29,000	28,600	29,700	29,000	29,700
Charpy Impact Strength	ft-lb	240 ft-lb	45 ft-lb	—	—	—
Thermal Properties						
CTE, linear 20ºC	µin/in-°F	9.61	6.28	6.78	6.39	6.39
CTE, linear 250ºC	µin/in-°F	9.89	6.61	7.61	7.22	6.78
CTE, linear 500ºC	µin/in-°F	10.4	6.78	8.11	8.11	7.72
Heat Capacity	Btu/lb°F	0.12	0.10	0.11	0.12	0.11
Electrical Properties						
Electrical Resistivity	nΩ-m	720	770	220	162	159

CTE Coefficient of Thermal Expansion

It should also be noted that the production version of the device may substitute some or all of these materials with lower-cost alternatives of equal or higher grades.

2.2.5.3. Bearing and Wear Pad Material

The following are the major requirements for the bearing selection:

- The bearings must be maintenance-free, requiring no lubrication.
- The bearings must be capable of supporting large loads.
- The bearing must be corrosion resistant in outdoor environments.
- The bearings should last the intended service life for the device.
- The cost and availability of the bearings should be reasonable.

Commercially available PTFE-based composites have an allowable bearing stress comparable to steel (~60,000 psi) and do not need lubrication (Table 8). These bearings provide good wear characteristics, exceptional corrosion resistance in most atmospheric conditions, and a low coefficient of friction (~0.04 on stainless steel). The shaft, pin, and posts of the lever arms have steel-backed, wound fiberglass / PTFE composite sleeve bearings. The axle bearing is a PTFE composite spherical plane bearing. The wear pads on the sides of the lever arm and the washers separating the clevis and rod end are cut from PTFE-based composite laminates.

Table 8: Composite Bearing Material Properties

Property	Duralon	Rulon ACM
Allowable Bearing Stress (psi)	20,000–60,000	40,000–76,000
Coefficient of Friction (static-dynamic range)	0.05–0.16	0.05–0.25
Maximum Operating Temperature (°F)	325	355
Coefficient of Thermal Expansion (µin/in-°F)	15	70

2.2.6. Strength Analysis of SLiM Components

By integrating a safety link into the SLiM design, we created a device that is 10% stronger than the transmission line on which the device is installed. During an overload, components of the SLiM device may become damaged, depending on the severity of the overload; however, the transmission line will break before the SLiM safety link breaks.

During normal operation, the device experiences line tensions up to 5,000 lb. The magnified loads experienced by the actuator will reach up to 30,000 lb. Individual components of the SLiM device were designed with these loads in mind, using safety factors that range from about 2 to 10. Furthermore, finite element stress analysis was performed on all major fabricated components to investigate stress concentrations (Figure 7: and Figure 8:). For all components, stresses fell well within acceptable limits. For details, see Appendix G.

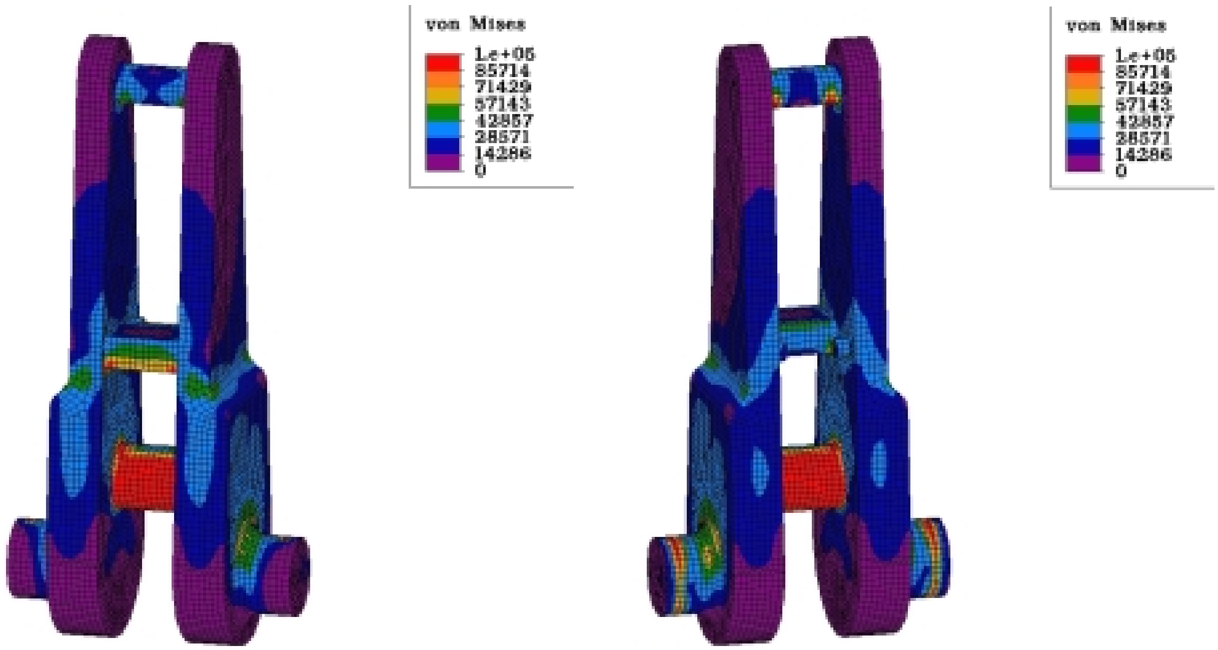

Figure 7: Finite element model showing von Mises stress contours for the lever arm.

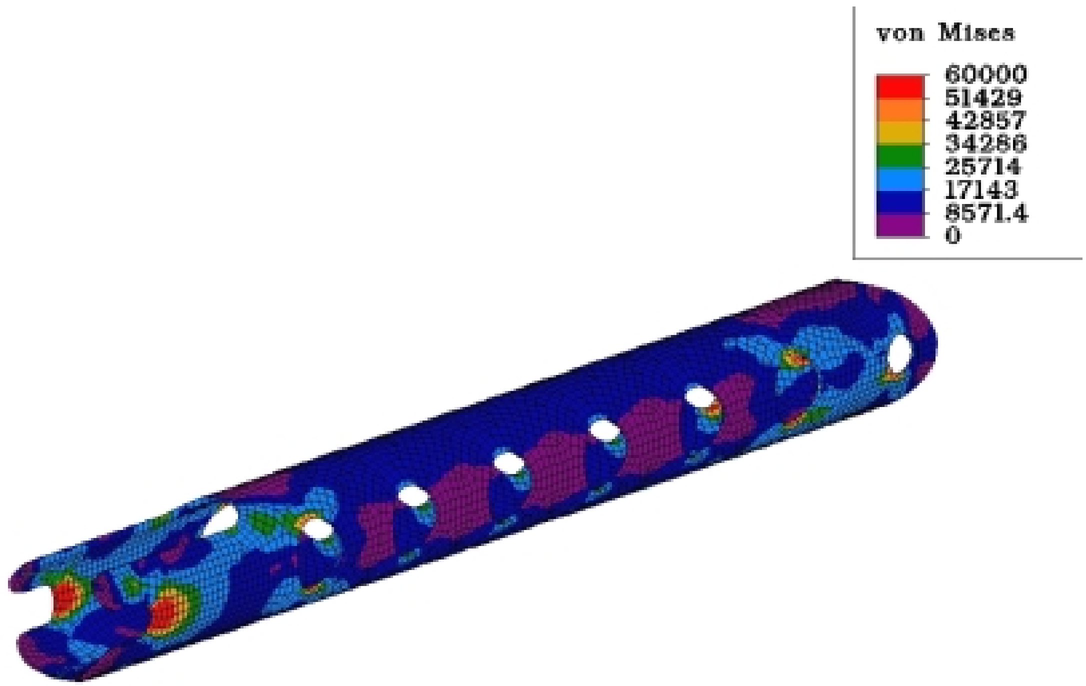

Figure 8: Finite element model showing von Mises stress contours for the SLiM body.

2.2.7. Electromagnetic Characteristics and Corona

Because the SLiM device will be in contact with high-voltage power lines, its generated electric field must be evaluated. A high electric field density can lead to corona, the ionization of air. Corona results in radio frequency noise and significant energy losses. The electric field of a device is a function of its electric potential, geometry, and surrounding conditions. In general, sharp edges produce high surface electric fields, leading to corona.

Although a strict set of rules for avoiding corona does not exist, we applied experienced-based practices common to the transmission industry in the design of the SLiM device. Most importantly, we avoided sharp edges whenever possible, and maintained surface electric field densities below 21kV/cm, the maximum value typically accepted by the industry.

We used finite element analysis software (Algor, Inc., Pittsburgh, PA) to calculate the electric field strength. To generate the finite element models, we took cross-sections with geometry most likely to cause corona from the solid model of the SLiM device. We created a 2-D mesh of elements surrounding the SLiM cross-section to a distance where the electric field potential was known to be equal to ground (0 volts). We set the electric potential at the surface of the SLiM cross-section to 133kV (230kV/√3) and performed a linear analysis to determine the electric field density around the device. For the worst cross-section, we performed one analysis with the device far from a tower and one with the device near a tower.

For the former case (far from a tower), the highest electric field density of 5.4kV/cm occurred near the tip of the lever arm (Figure 9: and Figure 6:). If the SLiM device were to be installed near a tower (4 meters), the field density would increase to 6.6kV/cm (Figure 7: and Figure 8:). Both values are well within the maximum targeted field density of 21kV/cm. (See Appendix H for more details.)

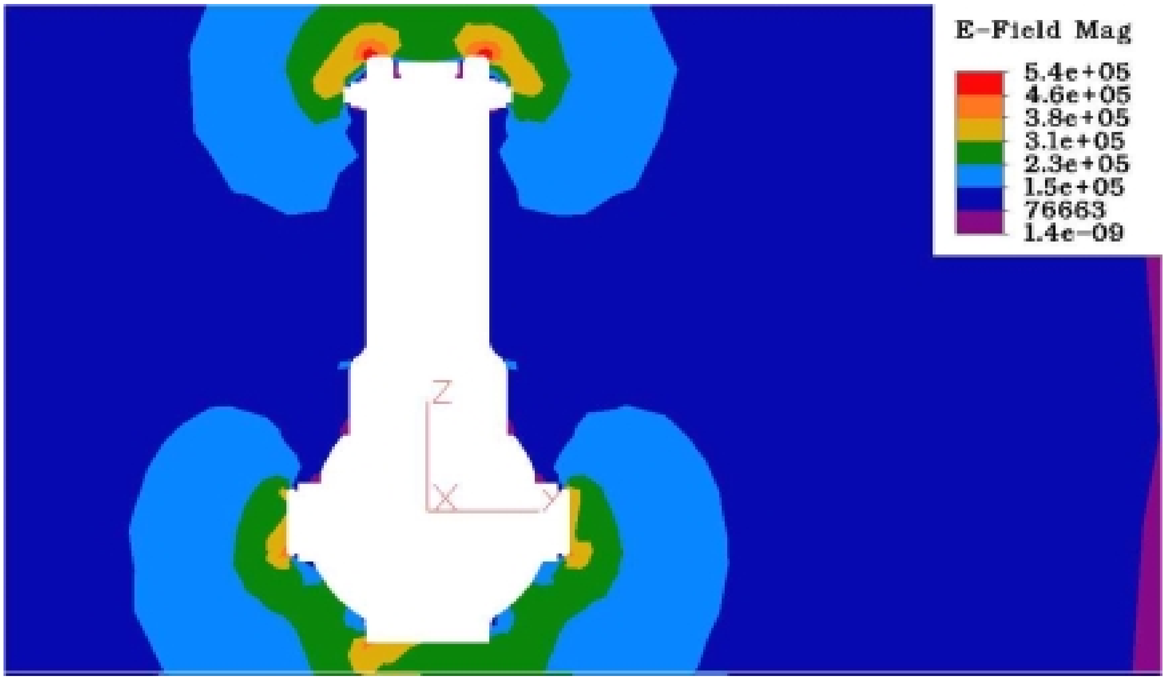

Figure 9: Electric field density surrounding the "worst case" cross-section of the SLiM device far from a tower.

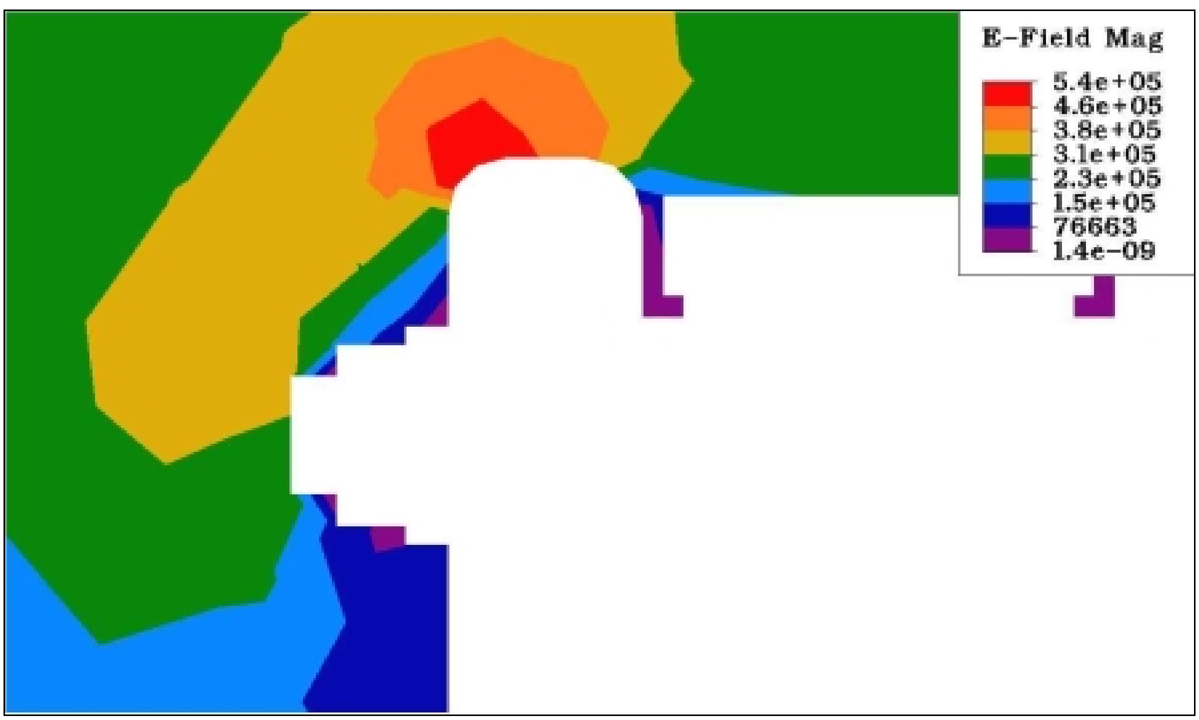

Figure 6: Closer view of the electric field density showing the location where corona is highest when the SLiM device is far from a tower.

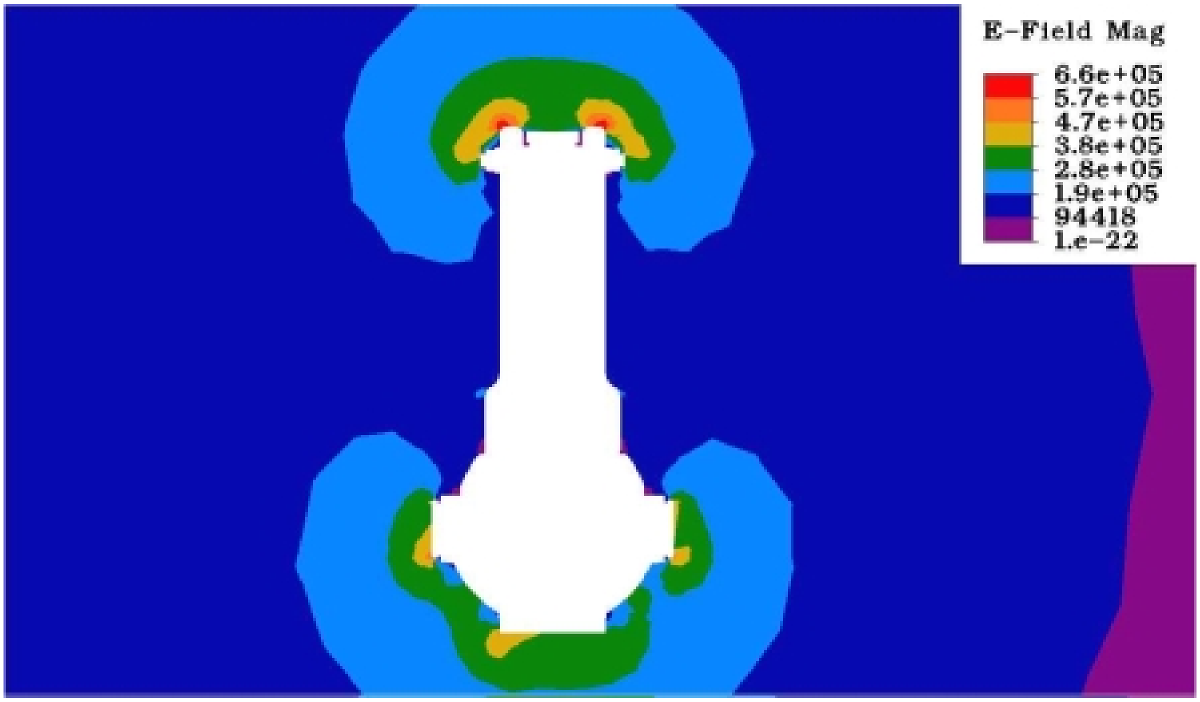

Figure 7: Electric field density surrounding the "worst case" cross-section of a SLiM device near a tower.

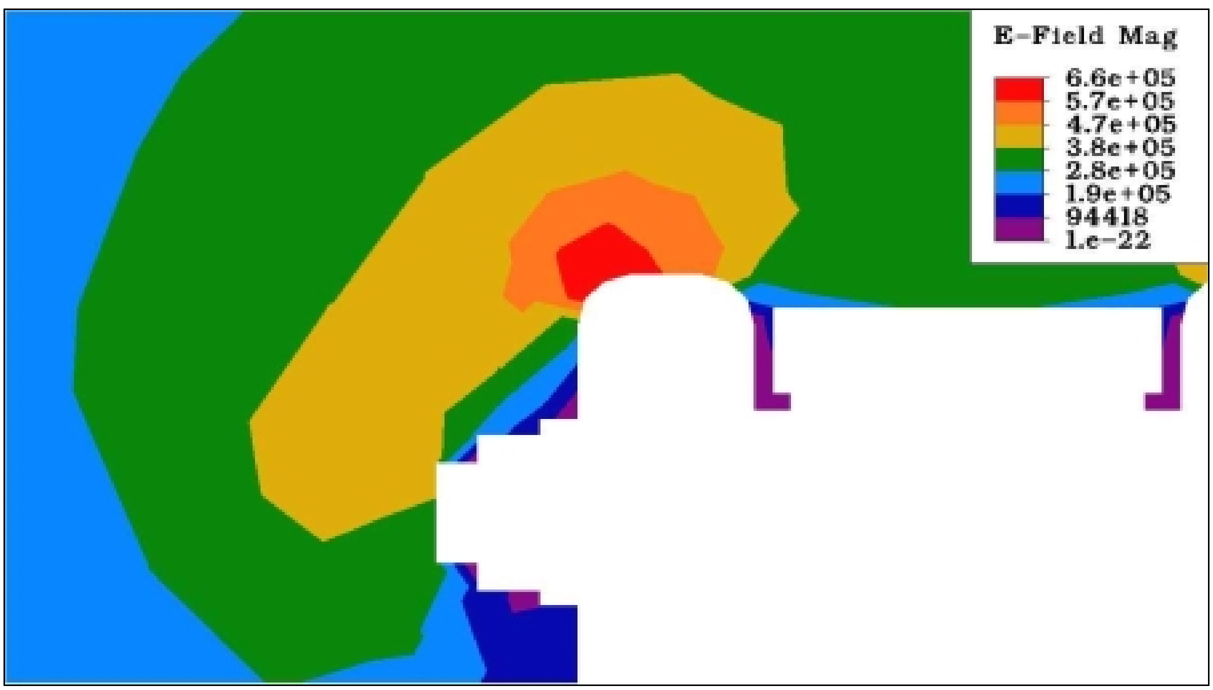

Figure 8: Closer view of the electric field density showing the location where corona is highest when the SLiM device is near a tower.

2.3. Operation

The same temperature change that leads to thermal expansion and sag in transmission line conductor activates the motion of the SLiM device (Figure 9:). This device is designed to have a range of motion up to 6" when the conductor temperature passes through the full transformation regime of the actuator.

Upon heating and sag mitigation, the device begins to retract and shorten the effective conductor length. Upon cooling, the device begins to open and release tension on the conductor. Examples of the magnitude of the sag reduction are given in Table 9 for a 600' and a 1,000' span of Drake conductor using a device with a 6" range of motion.

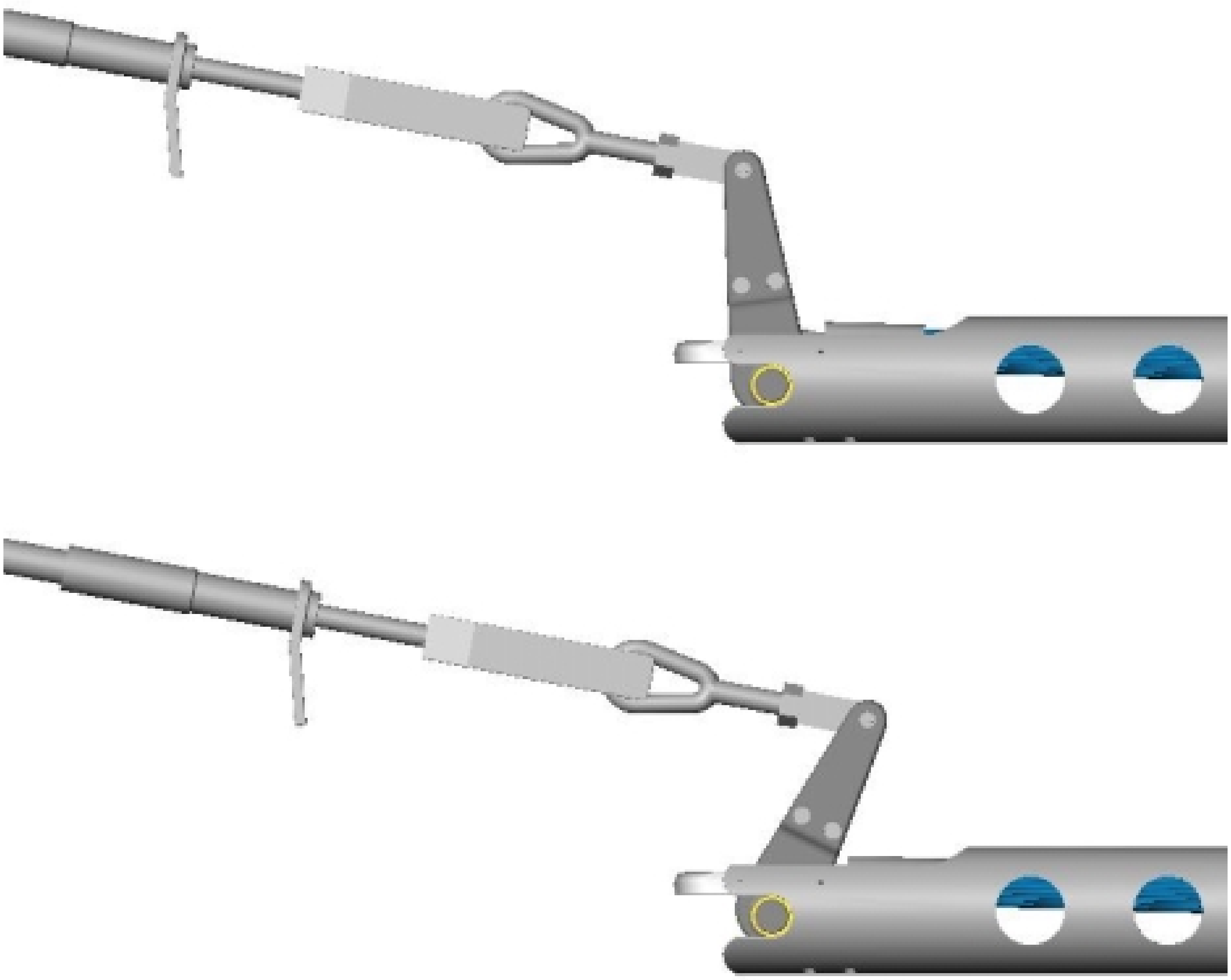

Figure 9: The SLiM device reacts to the same changes in temperature that produce excess sag in a transmission line. When the conductor temperature is low, the SLiM is open or extended (top). As temperatures rise, the actuator shortens, and the SLiM closes or retracts (bottom).

Table 9: Sag Mitigation for Drake Conductor

Span	Conductor Temperature*		Excess Sag due to Heating		Sag Reduction	
	Initial	Final	Without SLiM	With SLiM		
(ft)	(ºF)	(ºF)	(ft)	(ft)	(ft)	(%)
600	110	212	4.5	0.5	4	89
1000	110	212	6.0	2.8	3	50

* Ambient temperature equals 70ºF.

2.3.1. Impact on the Transient Behavior of a Transmission Line

Introduction of any device along a transmission line creates a discontinuity in characteristic impedance of the line. Discontinuities may cause reflections and standing waves along the transmission line. Thus, at some discontinuity points, transient voltage may exceed all other points along the line. These transient voltages may exceed the dielectric strength of the line insulators (2.5pu).

To gage the impact of the SLiM device on the transient behavior of a transmission line, we performed simulations of the transient voltages along a line containing SLiM devices (Appendix I). The industry standard Electro-Magnetic Transients Program (EMTP) [4] was used to ensure that transient voltage increases, if any, were not excessive.

The base configuration consisted of a 209km single-phase transmission line with an open transformer represented by an inductive load, a circuit breaker, and a 100kV generator (Figure 10:). Energizing the line (closing the breaker) in this configuration usually results in the highest transient voltages along the transmission line. We monitored voltages at all line and device terminals and a few points along the line, and recorded them in all simulations.

The SLiM device was modeled as a series resistance. We performed computations for the single phase line with a SLiM device installed at the middle of the line. We defined an overvoltage ratio for each simulation as the maximum voltage anywhere on the line containing the SLiM device, over the maximum voltage for the base configuration without the SLiM device.

The resistance ratio of the SLiM device is about 4.4 to Drake (795kcmil, ACSR), and about 5.5 to Marigold (1113kcmil, AAC), yet another commonly used conductor. Since simulations showed negligible effect (that is, small overvoltage ratio) on the transmission line for resistance ratios below 15 (Figure 11:), the SLiM device is expected to have negligible impact on the transient behavior of the line.

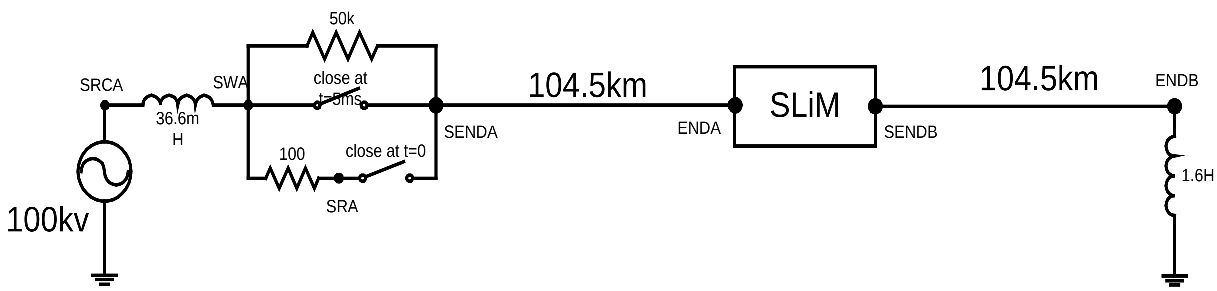

Figure 10: Model for transient voltage computation.

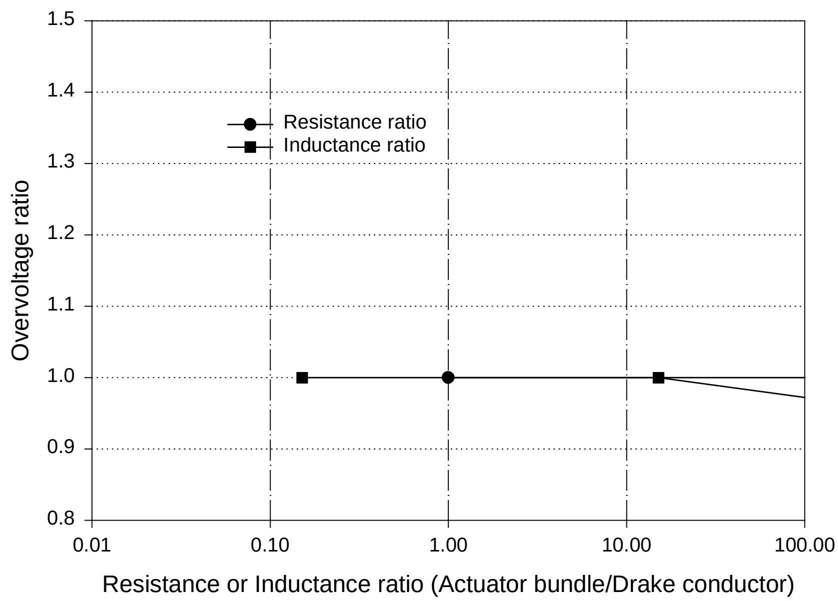

Figure 11: Overvoltage ratio on a single phase line resulting from a SLiM device vs. the resistance ratio of the device to the same length of Drake conductor.

2.3.2. Impact on the Vibration Characteristics of a Transmission Line

Two types of vibration are common on transmission lines:

- Aeolian vibrations are characterized by their high frequencies (5–60 Hz) and low amplitudes (1–2 conductor diameters) and are usually caused by laminar wind flows on the order of 0.5–10 m / s.
- Galloping is a low-frequency (0.1–1 Hz), large-amplitude vibration that usually results from moderate wind speeds passing over a large diameter conductor or an ice-covered conductor.

Because transmission line hardware must be designed to accommodate these vibrations, it is important to know if a SLiM device would increase the energy of oscillation on a transmission line experiencing aeolian vibration or galloping. To do this, we used an analytical model of a transmission line to determine if the introduction of a SLiM device would alter the line's dominant natural frequencies.

We performed a frequency analysis of a finite element model of a 750 ft span of Rail conductor (954 kcmil ACSR) at two temperatures—70°F and 200°F (Figure 12:). Rail conductor was used for this simulation since it is a common conductor and similar to Drake. We then repeated the analysis with a SLiM device near one support and again with a SLiM device located one quarter of the way along the span. The first 150 frequencies were considered, and we considered any frequency with a mass participation above 3% as a dominant frequency. (See Appendix J for more details.)

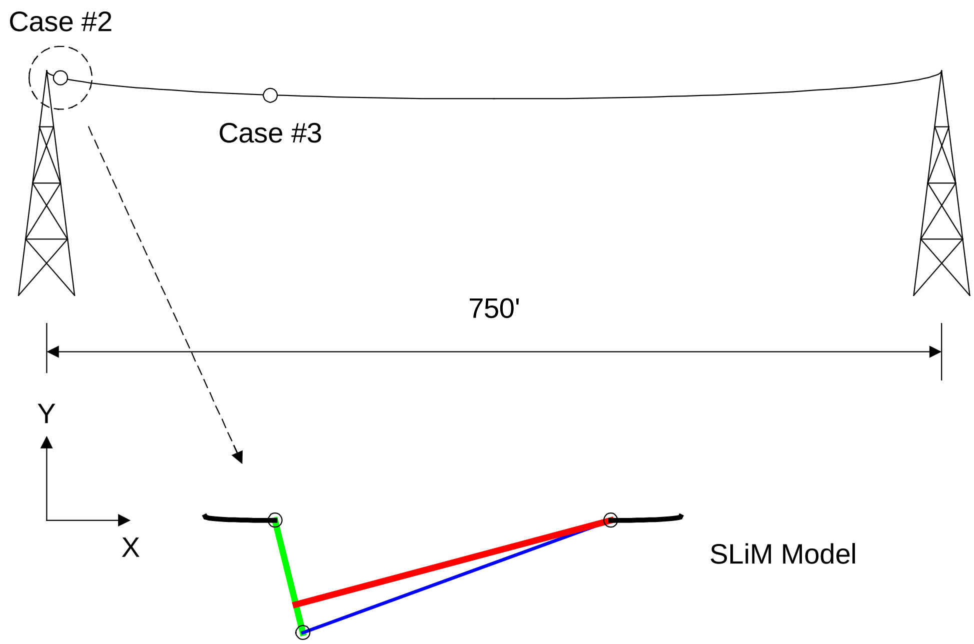

Figure 12: Model of 750' span of Rail conductor used to analyze the effect of the SLiM device on the vibration characteristics of a transmission line.

These analyses indicated that the SLiM device had a negligible effect on the natural frequencies of the transmission line in the vertical and lateral direction. Frequencies with the SLiM device were within 2% of the frequencies of the transmission line alone. In the longitudinal direction (along the axis of the span), the SLiM device reduced the dominant natural frequencies by over 50%, from about 5 Hz to about 2.2 Hz. This is not an unexpected result, since the shape of the SLiM device is similar to Richardson type aerodynamic drag dampers used to control galloping. Therefore it appears that for all cases, the effect of the SLiM device on the vibration characteristics of a transmission line range from negligible to beneficial.

2.4. Testing

Design and development of the full-scale SLiM device involved laboratory tests on several levels:

- A small-scale prototype was tested to demonstrate the feasibility of the SLiM concept.
- The shape memory alloy used in the actuator was tested to determine its shape memory behavior and fatigue life.

- The swage fittings that hold the shape memory alloy wires were tested to determine pull-out strength.
- Functionality testing was performed in the laboratory on a full-scale prototype to verify proper operation, to determine its range of motion, and to measure the transformation temperatures of the assembled device.
- Functionality testing was then performed on a live transmission line to demonstrate its sag reduction capabilities under real-world conditions.
- An electrical reliability test was performed to determine if the resistance across electric contacts in the device changed during repeated operation.

This section presents a synopsis of the methods and results for each test.

2.4.1. Laboratory Testing of a Small-Scale SLiM Prototype

Prior to using a full-scale prototype, we constructed and tested a small-scale prototype in the laboratory to verify the feasibility of the SLiM concept for mitigating sag. Details for this test are presented in Appendix K.

The small-scale prototype was a single lever-single magnification device (Figure 13:). The actuator, which was about 30" long, comprised shape memory alloy wires held in tension by wire rope socket assemblies. The cross-sectional area of the actuator was about 5% of that planned for the full-scale device. The shape memory wires had a transformation strain of about 2.3%. The lever arm magnified actuator length changes by a factor of ~5.6, giving the small-scale prototype a range of motion of about 4.0". Aluminum pipe was used for the body of the device.

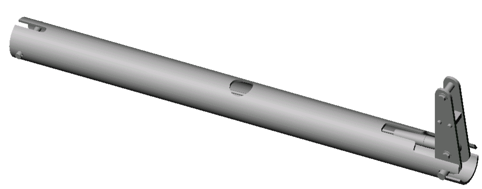

Figure 13: Computer rendering of the small-scale SLiM prototype.

The small-scale prototype was tested in a custom load frame (Figure 14:). A steel cable connected to a hydraulic pull-cylinder simulated conductor tensions; a current delivery system supplied the current to heat the actuator. Cable tension, lever arm displacement, actuator temperature, current and voltage were monitored during the two tests. The lever arm moved 3.64" and 3.80" in the first and second tests, respectively.

Figure 14: Photos showing the fully "open" position of the small-scale prototype when the actuator is cool (left), and fully "closed" position when the actuator is hot (right).

The test demonstrated that the SLiM concept for mitigating conductor sag was sound, and we therefore felt confident about developing a full-scale prototype.

2.4.2. Shape Memory Alloy Testing

Prior to selecting a specific alloy for the SLiM actuator, we performed an extensive search of the literature. We then selected and assessed a number of shape memory alloys that differed in composition and degree of cold work and heat treatment (Appendix L). We tested six alloys for transformation strain, transformation temperatures, hysteresis, cyclic creep, and cost. Due to time constraints, we performed fatigue tests on only two alloys that had already performed well in other tests. This process identified the best overall performer—a binary NiTi alloy.

To measure the shape memory behavior of this material, we thermally cycled small diameter wire specimens through the transformation regime under a constant stress ranging from 10-40 ksi. We used a custom load frame to apply stress to the specimens and measure displacements (Figure 15:). The load frame uses dead weight hanging from a lever to apply a force on the specimen. We measured deformation of the specimen using a drawstring transducer (Houston Scientific, model 1850-005). A 6V battery charger supplied the current for resistive heating, and we used a blower for cooling. We measured temperatures using J-type thermocouples and a data logger; and we recorded time, temperature, and displacement on a computer. Strain on a given cycle was defined as displacement divided by the length of the specimen at the beginning of that cycle. We constructed temperature-strain diagrams from the second cycle at each stress levels, giving a total of four curves for each specimen and determining transformation temperatures and transformation strains from these curves.

Figure 15: Custom load frame used for thermo-mechanical cyclic loading of wire specimens.

During fatigue testing, a single channel controller monitored thermocouple output (Omega, model CN4321); the controller cycled the battery charger on when the temperature reached 70°F and off when the temperature reached 250°F. To reduce cycle time, we placed the entire load frame inside a freezer (Figure 16:), which maintained an ambient temperature of 20–30°F. The blower ran continuously to circulate cool air over the specimen. Cycle time was approximately 1 minute. Cycles were recorded using an electric counter.

Figure 16: Freezer used to reduce cycle time during fatigue testing (left). 6V battery charger and temperature controller used for the fatigue testing (right).

For the selected shape memory alloy, transformation strain at the nominal operating stress of 30ksi was 3.4% on average (Figure 17: and Figure 18:). Although the alloy demonstrated a hysteresis upon thermal cycling, the hysteresis was smaller than other candidate alloys (Figure 18:). The S-N diagram developed from the fatigue tests showed that, at 30ksi, wire specimens had a fatigue life of 16,800 cycles (Figure 19:) when cycled through the entire transformation regime (below Mf to above Af). Partial transformation cycling through 50% of the transformation regime extended the fatigue life at 30ksi to 35,000 cycles. To determine a practical service life, we applied Minor's Rule with the following assumptions:

- There are 30 days in summer during which the actuator experiences one full transformation per day.
- There are 35 days in winter when temperatures remain below Mf and no transformation occurs.
- On the remaining 300 days, the actuator experiences one partial transformation per day, which covers 50% of the transformation regime.

Based on these assumptions, the SLiM actuator will have a fatigue life of ~100 years. (Appendix L contains more details.)

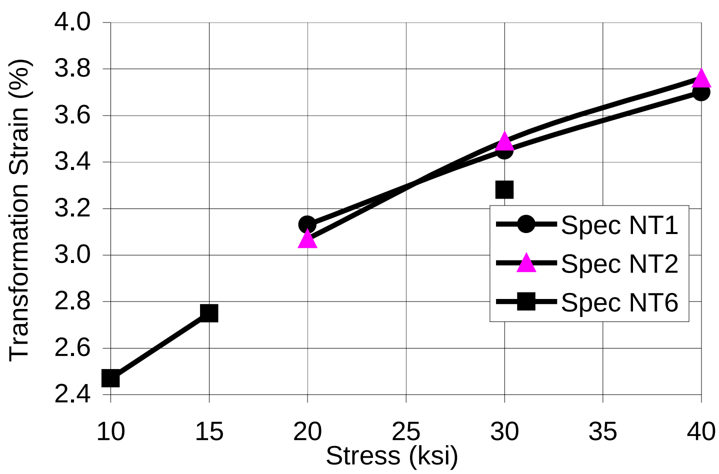

Figure 17: Transformation strain vs. stress. At the nominal operating stress of 30ksi, the average transformation strain was 3.4%.

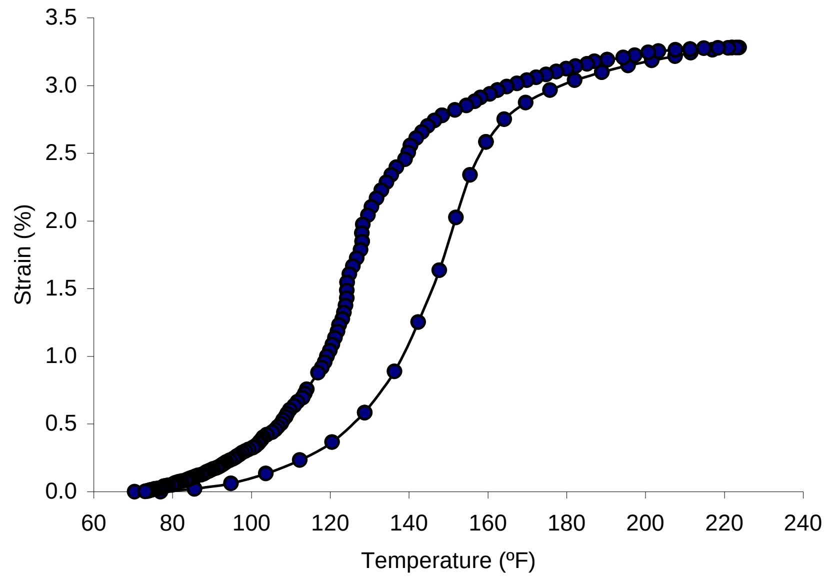

Figure 18: Temperature-strain diagram at 30ksi applied load showing a small hysteresis and a maximum strain of 3.3% for this specimen.

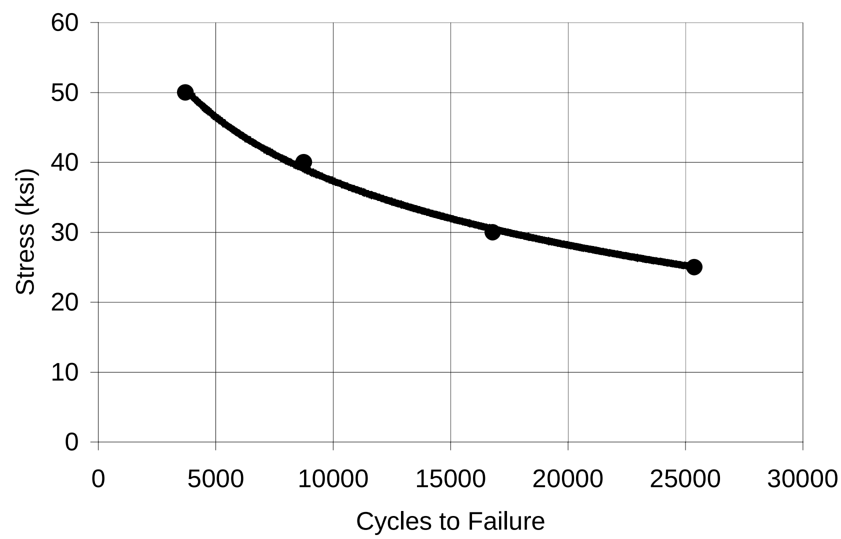

Figure 19: Fatigue life of the shape memory alloy used in SLiM. At the nominal operating stress of 30ksi, fatigue life was 16,800 cycles.

2.4.3. Pull-out Strength of Swage Socket

The custom swage sockets, which form the ends of the actuator, hold the shape memory alloy wires via a swage connection. Although the sockets are machined from a relatively soft steel to allow swaging, the large cross-section keeps the nominal stresses well below the yield strength. The most likely mode of failure would be when the shape memory alloy wires pull out from the swage sockets.

While developing the swage sockets, we conducted tension tests to determine the pull-out strength. After swaging a set of sockets onto 12" drill rods *(drill rods were used to simulate the NiTi)* (Figure 20:), we delivered the assembly to Cable Moore, Inc., a wire rope manufacturer in Oakland, California. The manufacturer pulled the assembly to failure in a tensile tester designed to test the strength of wire rope (Figure 21:). The pull-out strength of the current swage socket design was in excess of 65,000 lbs., well beyond the nominal working load of 30,000 lbs.

Figure 20: Swage socket assembly prepared for testing pull-out strength.

Figure 21: Tensile testing machine used to determine pull-out strength of swage sockets.

2.4.4. Functionality Testing of Full-scale Prototype (Laboratory Testing)

The objective of the laboratory functionality testing was to verify that the SLiM device produces the target range of motion when subjected to a typical line current of 1,000 amps and a line tension of 5,000 lbs. In addition, we measured the transformation regime of the assembled device to verify that it encompassed the target operating temperature range (110–212°F).

The prototype was tested in a custom load frame (Figure 22:). A steel cable, connected to a hydraulic pull-cylinder, simulated conductor tensions; and a current delivery system, capable of supplying over 1,000 amps, simulated conductor currents. Cable tension, lever-arm displacement, actuator temperature, current, and voltage were all monitored during the test. For a detailed description of the load frame, current delivery system, transducers used to collect data, and the data acquisition and storage system, see Appendix M.

Figure 22: Load frame and components for full-scale lab testing.

To test the functionality of the SLiM device, we loaded the full-scale prototype to 5000 lbs., such that the actuator was subject to a stress of about 30ksi. Approximately 1,000 amps were supplied to the device from the current delivery system. About 20% of the current passed through the actuator, heating it from room temperature to beyond the upper transformation temperature. The current was then turned off and the actuator was cooled to room temperature using fans. During heating and cooling, we maintained cable tension at a constant level by extending or contracting the hydraulic cylinder to compensate for the retraction / extension of the lever arm of the prototype. We removed the tension when the actuator temperature returned to 70ºF.

The functionality test on the SLiM prototype successfully demonstrated the operation of the SLiM device. Upon heating, the effective cable length was reduced by more than 5". Transformation temperatures represent the temperatures at which motion of the SLiM device is initiated and completed. We measured transformation temperatures of the SLiM prototype (Table 10) from the temperature-displacement diagram that maps the contraction and extension of the device during heating and cooling (Figure 23:). For a complete description of the test procedure and results, see Appendix N.

Table 10: Range of Motion and Transformation Temperatures of the SLiM Laboratory Prototype

Lever Arm Motion	M_F	M_S	A_S	A_F
5.0”	85°F	220°F	160°F	260°F

A_f = austenite finish temperature

A_s = austenite start temperature

M_f = martensite finish temperature

M_s = martensite start temperature

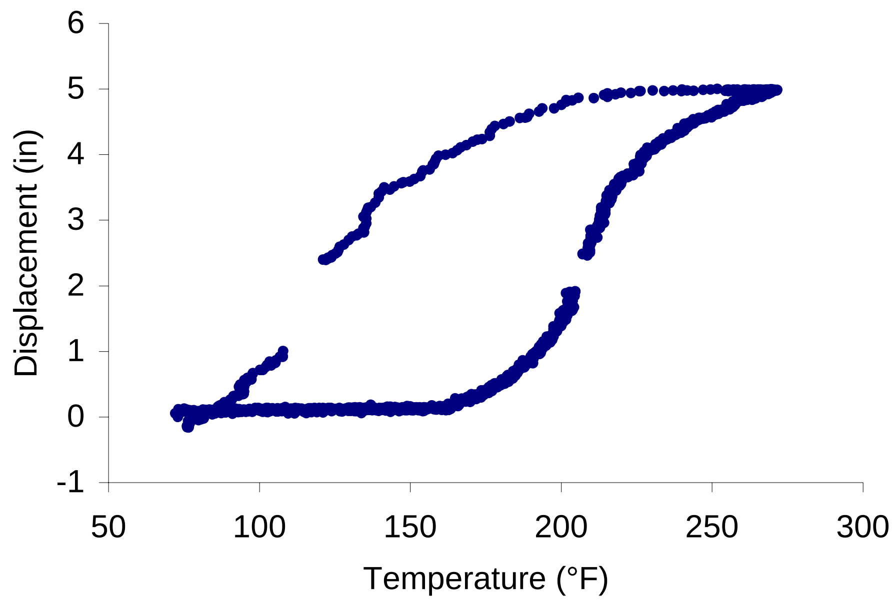

Figure 23: Temperature-displacement diagram for a lab test of the full-scale SLiM prototype.

2.4.5. Functionality Testing of Full-scale Prototype (Live Line)

To conduct the live-line functionality tests of the SLiM device, we identified 11 organizations that had testing labs, including utilities, a university, and independent research laboratories (Appendix O). Proposed testing methods were sent to each organization, along with a request for budgetary proposals to conduct the functionality testing. The Livermore training facility, which is owned and operated by Pacific Gas and Electric Company, was selected for the functionality testing.

The objective of the functionality test was to verify that the SLiM device reduced excess sag as designed, when operated on a live transmission line. The test was conducted on two parallel 500' spans of 795kcmil 54/7ACSR (condor) conductor. One span, with the device installed, acted as the test span, and the other as a control span. A current delivery system capable of 1,280 amps heated the conductor and device from ambient to the target temperature.

After installing the device (Figure 24), we brought both the test span and the control span up to the starting tension (5000 lbs.) and started the data acquisition. Tension, temperature, and current of both spans were recorded, as well as wind speed and direction, humidity and ambient temperature. We then ramped up the current to 1,000–1,280 amps and maintained that until the conductor temperature reached about 212°F. We shut off the current and allowed the spans to cool back to ambient. We measured the heights of the test and control spans midway between the poles relative to grade at the start of heating, periodically during heating (at 212°F), and at the end of cooling. The predicted effect of the SLiM device was calculated using in-house software based on IEEE Standard 738-1993.

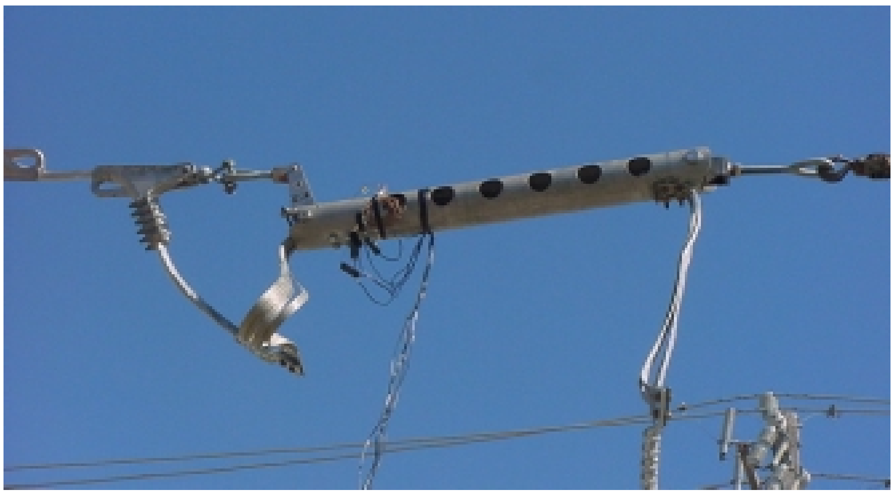

Figure 24: SLiM device installed on a live line for functionality testing.

During the test of the SLiM device, we measured the sag differential between the test and control spans at 44" (Figure 25). This closely matched the predicted value of 46" (Table 11). Accounting for cross-arm motion due to difference in test and control span tensions during heating, we determined that the total differential in sag created by the SLiM device would have been 50". This test successfully demonstrated the functionality of the SLiM device on a live transmission line. For a complete description of the test setup, procedure, and results, see Appendix P.

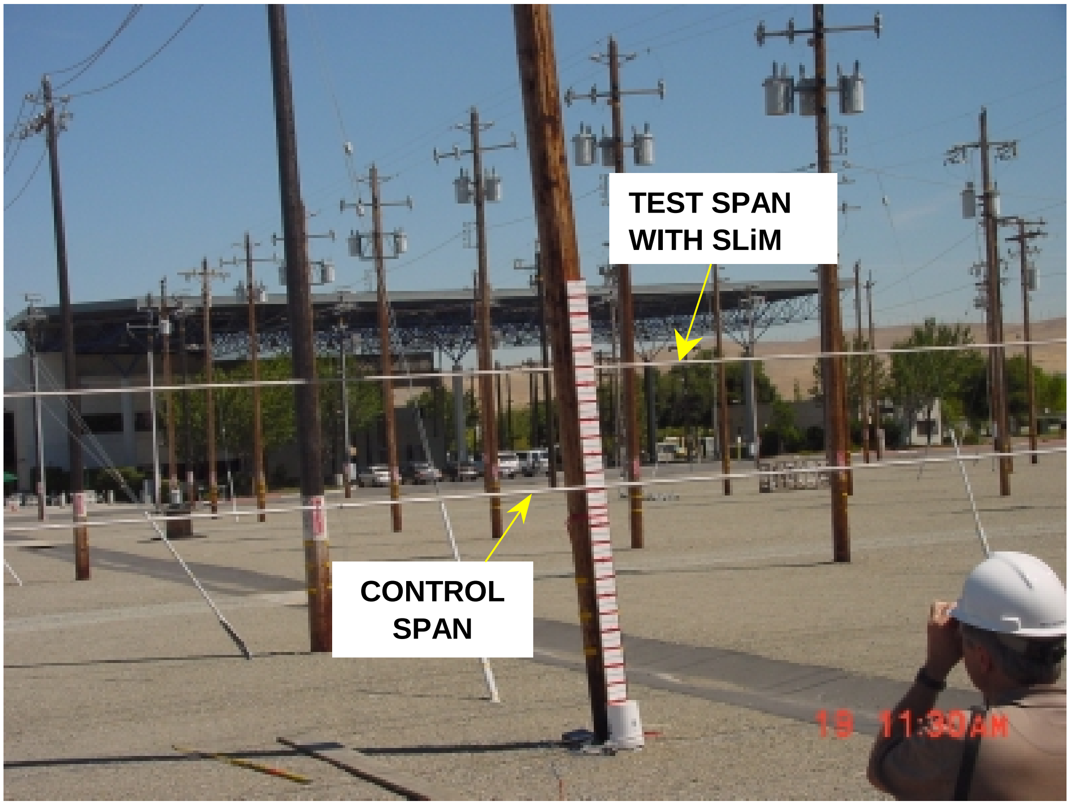

Figure 25: The sag differential between the test span (far) and control span (near) during the SLiM test. The total sag differential reached 44" by the end of the test.

Table 11: Tension, Sag, and Sag Differentials (SLiM Functionality Test)

	Control Span			Test Span			
	Tension (lb)	Height (in.)	Change in Sag (in.)	Tension (lb)	Height (in.)	Change in Sag (in.)	Sag Differential (in.)
Measured							
Cold	4731	152*	—	4808	151*	—	—
Hot	2685	87*	65	3747	130*	21	44

* Height from ground at midspan.

2.4.6. Reliability Testing

The SLiM device is intended for use on overhead transmission lines in all outdoor environments. Operational factors will subject the devices to currents, temperatures and forces which will vary in an irregular cyclic manner. Environmental considerations will subject the device to potentially corrosive factors such as ocean salt spray, acid rain and industrial pollution. The SLiM design must be tough enough to resist fatigue and corrosion and to maintain its sag reducing capabilities throughout the life of the device.

Design criteria established early in the SLiM project addressed each of these long term considerations. The end result was a robust design intended for a long service life. To determine the service life of the device, and to report on its reliability, four tests were conducted which investigated the fatigue behavior, reliability of the electrical connections, corrosion resistance, and overall cyclic performance. A description of each test and their results are presented in this report. A detailed discussion of the materials, setup, procedures and results for each of the following tests is given in Appendix Q.

2.4.6.1. Fatigue Behavior

Fatigue tests of the shape memory alloy used in the actuator of the SLiM device were conducted during the materials selection phase of the project. After selection of a shape memory alloy, additional tests were conducted to evaluate the effect of partial transformation cycling on the fatigue life of the SLiM device. Based on results presented in Section 2.4.2, the shape memory wires used in the SLiM actuator have a fatigue life of approximately 100 years. Full details of the test procedures and results are presented in Appendix L.

2.4.6.2. Electrical Connectivity Test

A limited electrical connectivity test was performed on components that will not change from the prototype to the production version of the SLiM device. The two electrical contacts that transmit current between the transmission line and the device are based on standard NEMA bolted connectors commonly used in the utility industry. Although expected to perform reliably, these connections will still be tested once their location and configuration are established for the production SLiM design. At this time, only the electrical connection between the shape memory wires of the actuator and the swage fittings will be tested since this connection will be the same in the prototype and production versions. A full connectivity test will be performed on the entire SLiM device once the production version has been fabricated.

The objective of the electrical connector reliability test was to determine if the contact resistance between the shape memory alloy wires and the swage fittings would increase during service. Per IEC Standard 61284-1997-09, the electrical connections within a device will be deemed “reliable” if: “a graph of resistance against the number of cycles shall demonstrate with a reasonable probability that the rise in resistance over the last 0.5N cycles is not more than 15% of the average resistance over the same period.”

The SLiM device was held in a custom load frame and placed under a tension using a simple hydraulic system (Figure 26:). A manual hand pump was used to partially fill a bladder style accumulator and to activate a hydraulic pull cylinder which puts tension on the device. Once the starting tension was established, a ball valve was closed, isolating the hand pump and reducing the hydraulic system to the pull cylinder and the accumulator. During cycling, the length change of the device was accommodated by movements of the hydraulic cylinder. As the device shortened, the hydraulic cylinder lengthened by pushing hydraulic fluid into the accumulator. As the device lengthened, the hydraulic cylinder shortened and fluid flowed back from the accumulator to the cylinder. A 1000 amp current delivery system, operated by a closed loop temperature controller, was used to heat and cool the device cyclically between 110°F and 212°F. At the low temperature of 110 °F, the tension on the device was about 4400 lb. At the high temperature of 212 °F, the tension on the device was about 5000 lb. The current was measured with a handheld ammeter (TPI Inc., Model CAT III). The voltage across the actuator, from one swage fitting to the other, was measured with a highly sensitive multimeter (Hewlett Packard, Model 3457A). Resistance was calculated from current and voltage measurements. Measurements were taken periodically at the high and low temperatures during the 525 cycle test.

Figure 26: Load Frame & components for reliability testing.

The resistance across the SLiM actuator did not change within measurement resolution during the 525 cycle test. Resistance did not change by more than 15% of the mean resistance over the last half of the cycles (Figure 27). The mean (± standard deviation) resistance was 1.43 ± 0.087 mΩ at 110°F, and 1.40 ± 0.037 mΩ at 212°F.

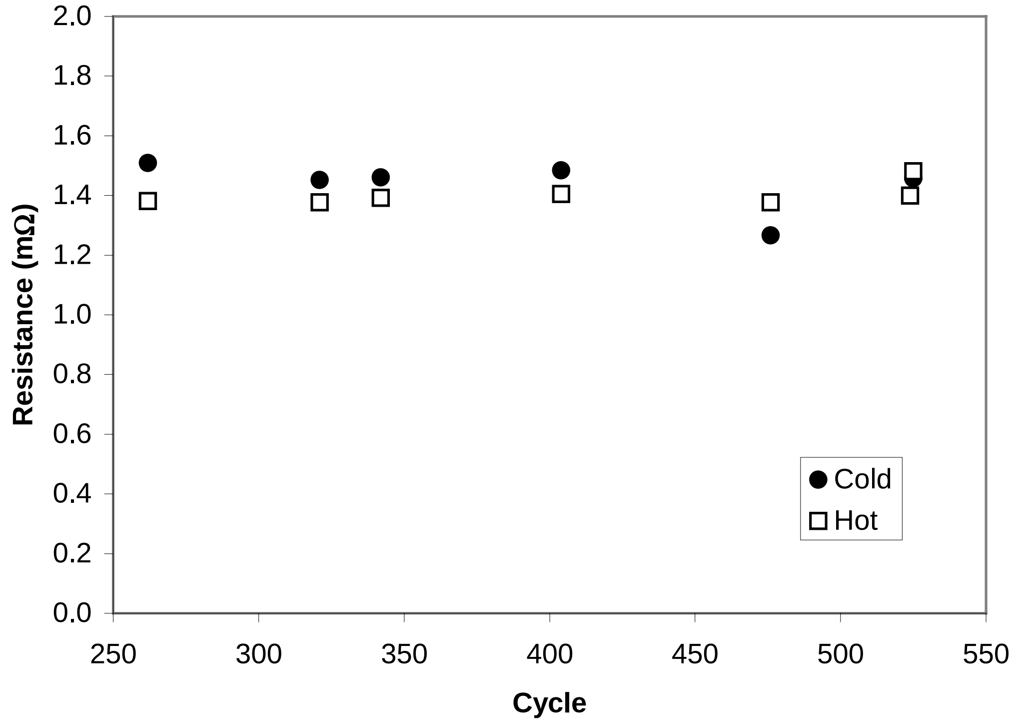

Figure 27: Resistance across the SLiM actuator was constant within measurement precision throughout the electric reliability test.

The contact between the shape memory wires and the ends of the SLiM actuator is accomplished by a swaging the ends onto the wires using a hydraulic press. Not only does this provide a strong mechanical hold, it also ensures excellent electrical connectivity. As expected, the resistance across the electrical connections within the SLiM device demonstrated no noticeably change after 525 thermo-electric load cycles, indicating that the swage connections at the ends of the SLiM actuator provide a reliable electrical connection.

2.4.6.3. Corrosion Test

Since SLiM devices will be installed on transmission lines in a variety of outdoor environments, the devices will be subject to corrosion. All components of the SLiM device were designed against environmental corrosion. Stainless steel frame components, composite bearings and nickel-titanium actuator wires all provide excellent corrosion resistance. The only area that has not been studied by others for corrosion resistance is the bi-metallic junction between the NiTi wires and the stainless steel swage ends. The objective of this test was to determine if the connection of these two metals lead to galvanic corrosion.

Swaged connections between the NiTi wire and the stainless steel housing were immersed in various solutions including:

- a solution of tap water and salt (NaCl) concentrated at 3% with an initial pH of between 5.5 and 6.0, and a final pH of 6.0 or greater,
- actual ocean water from San Francisco Bay with a pH of greater than 6.0,

- rain water with a 4% H_2SO_4 solution to simulate acid rain with a initial and final pH of between 4.0 and 4.5.

The solutions were then partially immersed in a hot water bath to maintain an average operating temperature of 140°F. Figure 28: below shows this setup with the sample bottle caps protruding through the tank cover and the heater in the foreground. Specimens were comprised of a 3” length of 1/8” diameter NiTi wire swaged into a stainless steel closed swage stud such that ~1” of the NiTi wire protruded from the fitting. One specimen was placed into each of the three solutions. Testing was conducted over a 3-week period.

Figure 28: Corrosion Test Setup Showing Tank, Tank Heater, and Individual Specimen Bottles.

Specimens in acid rain and ocean water showed no signs of corrosion (Figure 29:). In the NaCl solution, an iron oxide residue formed on the specimen at the junction between the NiTi and the stainless steel sleeve. Since neither NiTi nor stainless steel are prone to rust, it was determined that a small piece of steel or iron based residue must have been trapped between the NiTi wire and the stainless steel during the swaging process. An additional specimen was tested in the NaCl solution and exhibited no corrosion buildup.

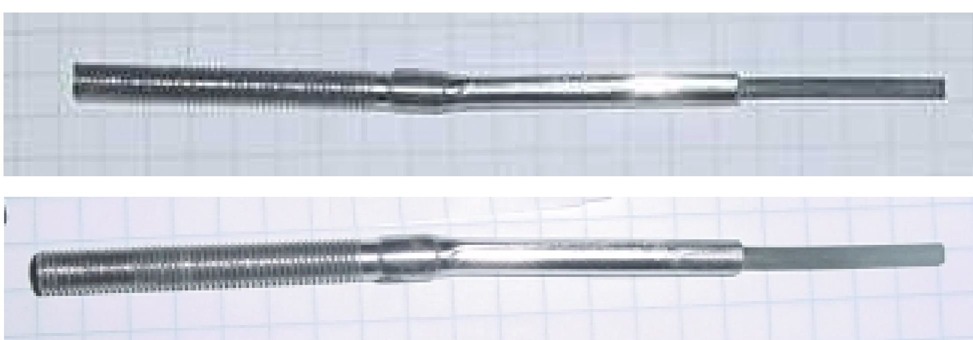

Figure 29: Sea water specimen (NT2) before (top) and after (bottom) corrosion testing.

2.4.6.4. Overall Cyclic Reliability/Performance

This reliability test was intended to determine if the integrity of the device is affected by thermo-mechanical cycling. Since the electrical connectivity test described above also subjects the device to 525 full operating cycles, the two tests were performed concurrently. After conclusion of all tests, the device was inspected for signs of distress (deformation, cracking, discoloration, etc.) to gage the overall reliability of its components.

Overall, the performance of the device proved to be very consistent across 525 operating cycles, suggesting that the device will perform reliably over its service life. The cyclic reliability test identified two joints requiring improvement. More bearing area was required at the joint between the lever and the body to lengthen the life of the PTFE liner in the bearing. At the other end of the device, snap rings, intended to keep the shaft about which the actuator rotates centered, were replaced by a bolted connection to counter thrust loads produced by dilation of the body when loaded. Both problems were relatively minor, and had only a small effect on the functionality of the device. The production design of the SLiM device resolves both issues, and we are confident that further cyclic testing of the production version will demonstrate the overall reliability of all components in the SLiM device.

2.4.6.5. Summary of Reliability Test Results

Based on fatigue test results of the shape memory alloy comprising the SLiM actuator, the safe service life of the SLiM device will be approximately 30 years. During this service life, the device, which will be comprised almost entirely out of 316 stainless steel and NiTi alloy, will likely show little to no signs of corrosion. In particular, our tests have shown that there should be no galvanic corrosion between the two metals. Since the resistance across the NiTi-Steel junction in the actuator did not change during our 525 cycle test, the electrical connections should also function reliably and consistently. Overall, the SLiM device is expected to operate safely and reliably over its intended service life.

3.0 Other Products

3.1. SmartConductor

In its current configuration, the SmartConductor is a ~6' length of conductor that shortens when heated due to its shape memory alloy core (Figure 30). Constructed using standard industry connectors, the device is *assembled* rather than *fabricated*. With about 30% of the range of motion of the SLiM device, the SmartConductor is a lower-cost alternative to the SLiM device for applications that require less sag mitigation. For details about the design and testing of the SmartConductor, see Appendix G.)

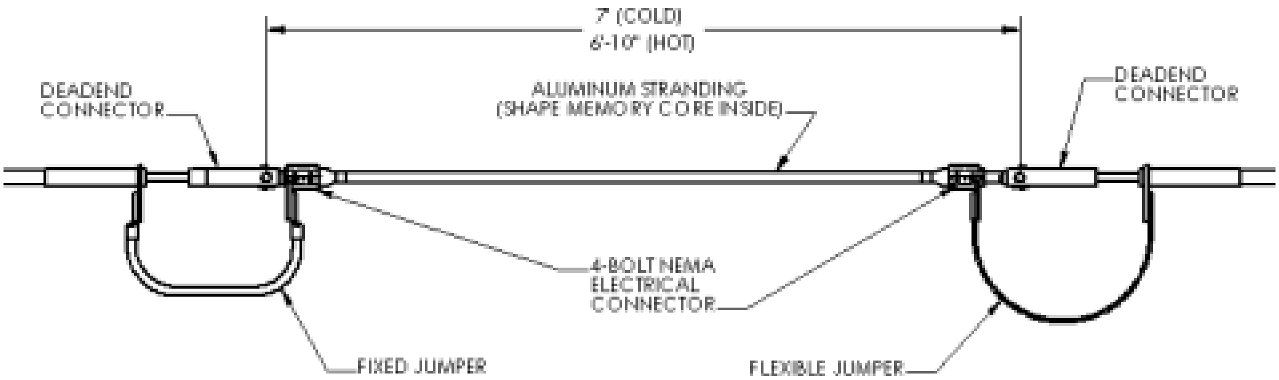

Figure 30: Schematic of the SmartConductor.

3.1.1. Description of Device

SmartConductor is similar to a length of ACSR conductor in which the steel reinforcing core is replaced by shape memory alloy wires. The shape memory wires were wrapped in the aluminum stranding from a Condor conductor (Figure 31). The assembly was held tightly at the ends by bolted aluminum compression fittings (Figure 32:).

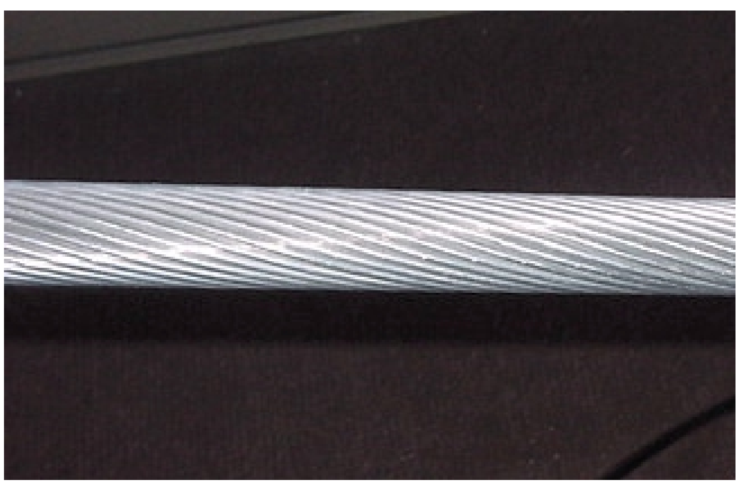

Figure 31: Aluminum stranding used in the SmartConductor. There are 54 wires, each 0.1213" in diameter.

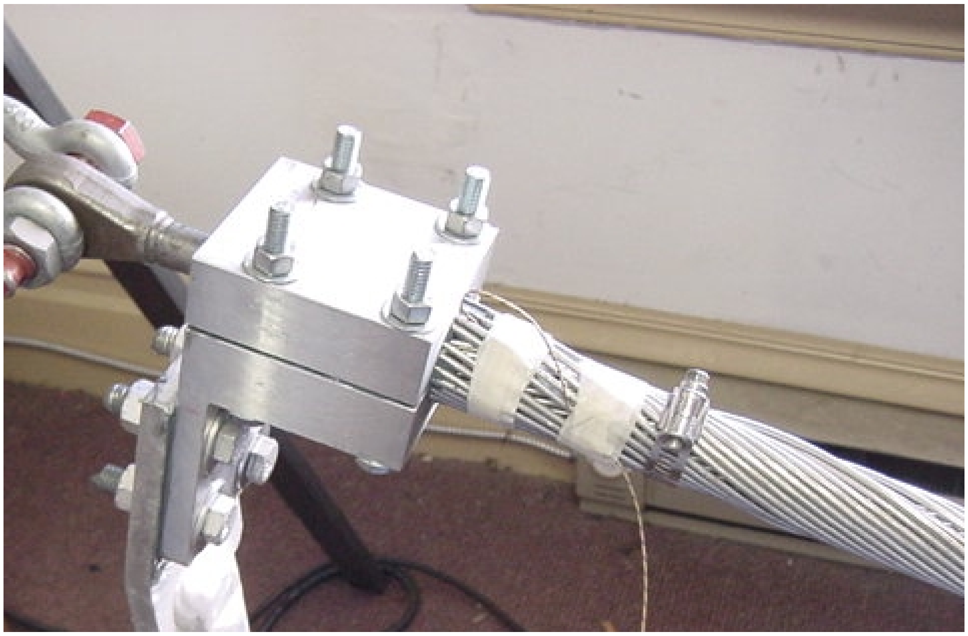

Figure 32: Compression fitting used in the SmartConductor.

3.1.2. Current Path

Heating of the SmartConductor, and thus the phase transformation of its shape memory wires, is accomplished by passing current through the aluminum stranding and heating the NiTi core via conduction. On the slider side of the SmartConductor, current is carried from the dead-end connector on the transmission line to the SmartConductor through a standard flexible connector. This jumper is bolted to both the transmission line dead end and the SmartConductor terminal using a standard 4-bolt NEMA connection. A standard aluminum jumper, attached to the SmartConductor terminal on one end, and the transmission line dead end on the other complete the current path of the SmartConductor. Although the aluminum stranding and the NiTi wire core are in contact, almost 100% of the current passes through the aluminum stranding due to its much lower resistance. To prevent arcing, we maintained all components of the device at the same electric potential via metal-to-metal contact.

3.1.3. Operation

The SmartConductor is designed to have a range of motion up to approximately 2" when the temperature passes through the full transformation regime of the NiTi wires. Upon heating and sag mitigation, the device begins to retract and shorten the effective conductor length when the temperature reaches approximately 160ºF. Full retraction is reached at approximately 260ºF. Upon cooling, the device begins to open and release tension on the conductor at about 220ºF, and is fully open at 85ºF. Examples of the magnitude of the sag reduction are given in Table 12: for a 500' and a 1,000' span of Condor conductor using a device with a 1.8" range of motion.

Table 12: Sag Mitigation for Condor Conductor (Ambient Temperature Equals 70ºF)

Span (ft)	Conductor Temperature Initial (ºF)	Conductor Temperature Final (ºF)	Excess Sag Due to Heating Without SLiM (ft)	Excess Sag Due to Heating With SLiM (ft)	Sag Reduction (ft)	Sag Reduction (%)
500†	110	212	3.6	2.6	1.0	28
1000‡	110	212	4.1	3.6	0.5	12

† Approximate span that will be used during field testing of SLiM device.
‡ For long spans, longer or more SmartConductor segments may be used to provide the desired sag reduction.

3.1.4. Laboratory Testing

A functionality test was performed on the SmartConductor using a custom load frame to simulate line tensions (Figure 33). A simulated line tension of 2,600 lbs. was applied to the SmartConductor using a hydraulic pull cylinder. A current delivery system passed current through the aluminum stranding. After the SmartConductor reached a temperature above 250°F, we terminated the current and cooled the device with the assistance of fans. Temperatures were measured with type-J thermocouples, and the displacement of the device was measured using a draw string transducer. For a full description of this load frame and the data acquisition system, see Appendix M. The total motion of the SmartConductor was 1.64".

Figure 33: Functionality testing of the SmartConductor.

3.1.5. Live-Line Testing

Functionality of the SmartConductor was tested on a live line at Pacific Gas and Electric Company's Livermore training facility. Setup and test procedures were similar to those discussed for live-line testing of the SLiM device, with one exception: Both the test and control spans were tensioned to 2,700 lbs. at the beginning of the test (Figure 34). Sag differential between test and control spans was measured at 10" (Table 13:, Figure 35) which agreed with the predicted value of 10".

Table 13: Tension, Sag, and Sag Differentials (SmartConductor Functionality Test)

	Control Span			Test Span			
	Tension (lbs.)	Height (in.)	Change in Sag (in.)	Tension (lbs.)	Height (in.)	Change in Sag (in.)	Sag Differential (in.)
Measured							
Cold	2917	99*	—	2925	97*	—	—
Hot	2073	42*	57	2202	50*	47	10

* Height from ground at midspan.

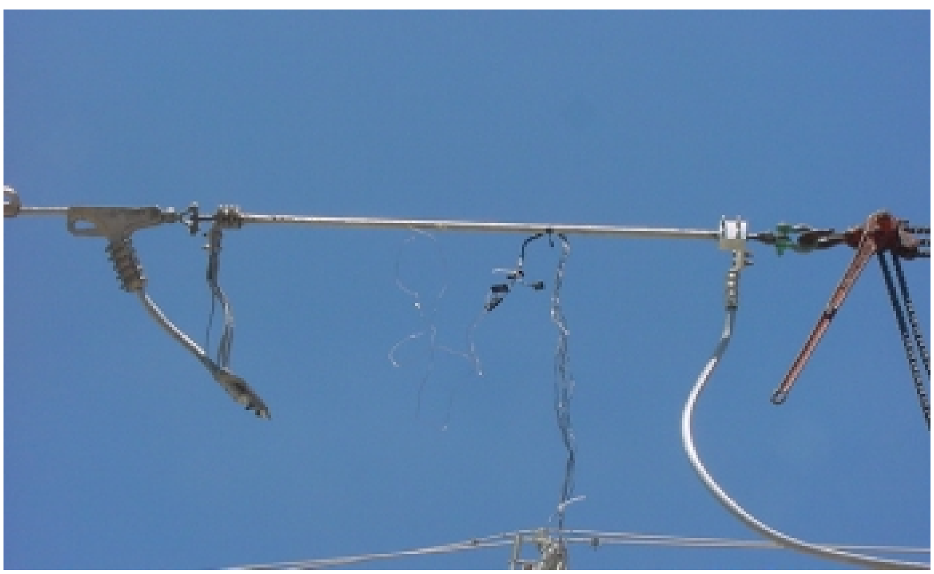

Figure 34: SmartConductor installed on a live line for functionality testing.

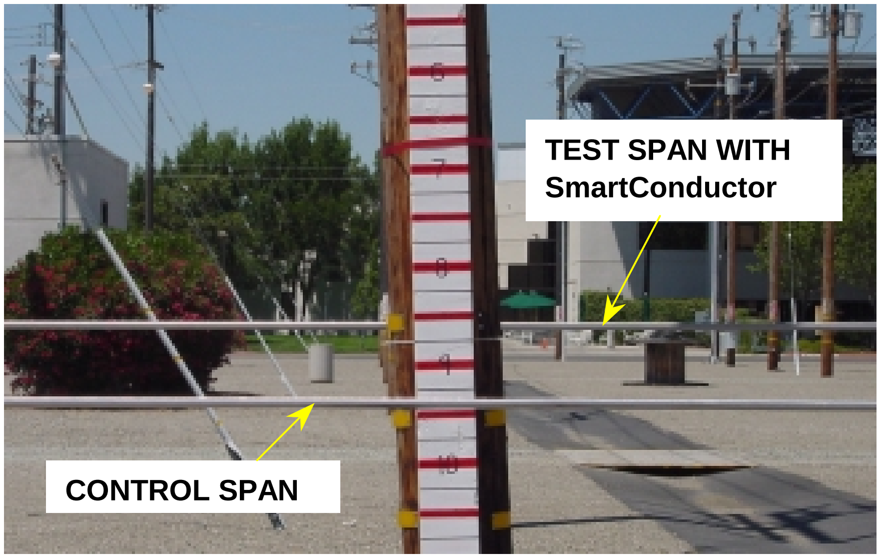

Figure 35: The differential in sag between the test span (far) and control span (near) reached about 10" during the SmartConductor test.

3.2. Complex Terrain Modeler

Optimizing the use of SLiM devices in actual applications requires a tool for determining where they will be most effective in a transmission line section. Unless both ends of a span are anchored, as with road and waterway crossings, insulator swing allows tension in adjacent spans to equalize. Although this reduces the effect of a single device on the span in which it is installed, insulator swing can be advantageous by allowing a single SLiM to mitigate sag on several spans. Insulator swing also permits the device to be installed on adjacent spans when a problem span is less accessible.

To determine the optimal location and number of SLiM devices required to resolve a sag problem, we needed a simulation technique that considers the entire transmission line section. To address this need, we developed and tested a complex terrain modeler using COSMOS finite element software (Structural Research and Analysis Corporation, Santa Monica, California).

The complex terrain modeler consists of a finite element model using three-dimensional truss elements for the conductor and beam elements for the insulators. The actuator of the SLiM device is simulated with a truss element with a negative coefficient of thermal expansion, and the linkages of the SLiM that magnify the actuator length change are modeled with beam elements. The position and number of spans, initial sag on each span, temperature change, type of insulator, and number and location of SLiM devices are all input by the user. The complex terrain modeler then simulates the effect of heating on the entire system, accounting for insulator swing and action of the SLiM devices.

Correct operation of the complex terrain modeler was first verified with no SLiM devices. Three models were then constructed, each having different pole configurations and initial and final conditions. An example of one of the models used is shown in Figure 36. Sag and tension for each span were simulated, then compared against values calculated using commercial software (SagSec, Power Line Systems, Inc., Madison, Wisconsin), and against values calculated by hand using catenary equations and a thermal balance (IEEE Standard 738-1993). Simulated values were within about 1% of calculated values, demonstrating the accuracy of the modeling technique.

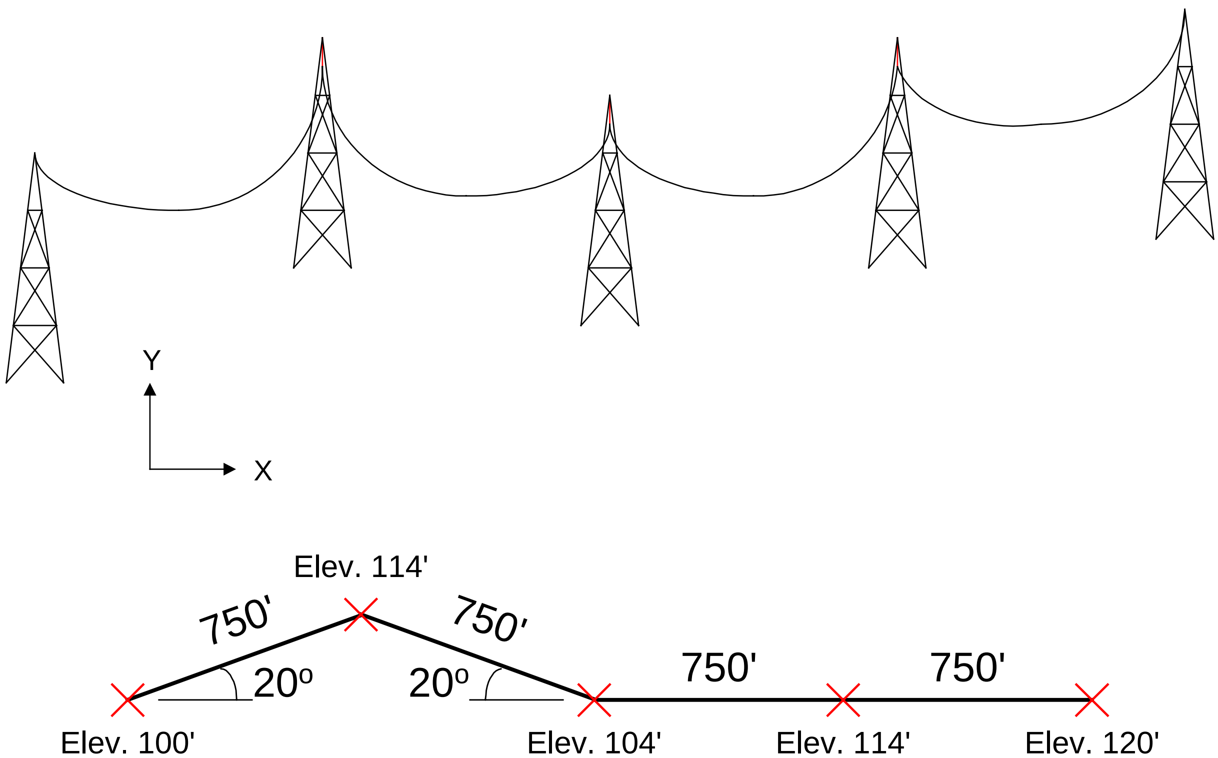

Figure 36: Four span (starting from left with span #1) transmission line section of Rail conductor (954kcmil ACSR) used to validate the complex terrain modeler.

To demonstrate how the complex terrain modeler can be used, we analyzed three more scenarios, assuming sag problems on at least one span in the transmission line section. These scenarios included a single 750' span of Rail conductor, a section of four 750' spans of Rail, and a section of ten 600' spans of Rail. For a four-span section (Figure 36), one device reduced sag on all four spans with reductions in sag ranging from 28" to 111" (Table 14). For full details of the single and four span simulations and their results, see **Appendix R**.

Table 14: Results of the Complex Terrain Modeler on a Four-Span Section of Rail Conductor

Span	Sag Without SLiM (in.)		Sag with SLiM (in.)		Reduction in Sag (in.)
	70°F	200°F	70°F	200°F	
1	83.52	166.44	89.97	144.33	28.56
2	101.28	186.24	106.46	119.98	71.44
3	115.56	201.84	102.92	77.93	111.27
4	136.20	223.56	126.38	138.68	75.06

For the ten span section, span 5 was assumed to have a sag problem. If only one device was placed on span 5, insulator swing will distribute the sag reduction effect to all spans in the section. Instead of several feet of sag reduction on one span, we obtain several inches of sag reduction on all spans, with the greatest reduction on span 5.

We then asked the question: How much additional benefit is derived by adding more SLiM devices to spans adjacent to the troubled span? To provide a basis for comparison, normalized with respect to conductor type, span characteristics and temperature change, *100% sag reduction capacity* was defined as the reduction in sag on span 5 when one SLiM device was installed on each of the ten spans. Note that more than 100% sag reduction capacity could be obtained by installing more than one device on a span.

One device on span 5 reduced one-quarter as much sag as ten devices; therefore, one device provided 25% sag reduction capacity. With one device on span 5, and one on neighboring span 6, we obtained 40% sag reduction capacity. To obtain 70% sag reduction capacity, five devices are needed. Although each application should be modeled in order to determine the optimal number and placement of SLiM devices, normalized results such as those shown in Figure 37 can assist with quick estimates on the number of devices a problem section may require. See Appendix S for further discussion of the ten span model.

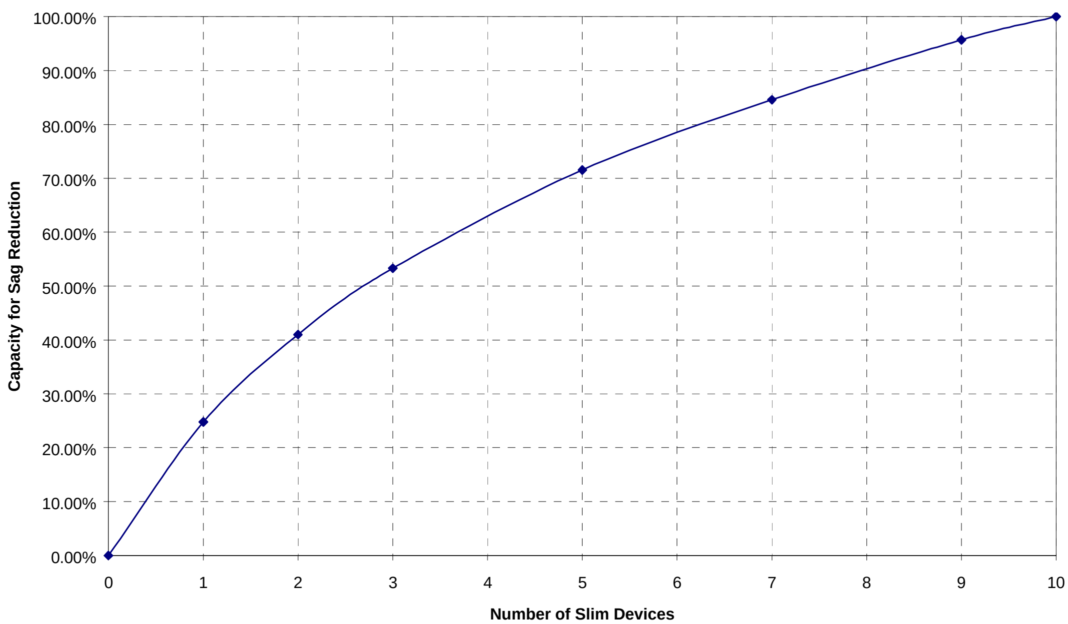

Figure 37: Percent capacity to reduce sag on a ten span section as a function of the number of SLiM devices.

4.0 Project Outcomes

Through market research and design and testing iterations, the SLiM project developed and successfully demonstrated a product that meets the utility market's need for a solution to excess sag in transmission lines.

Following are significant project outcomes:

- Market surveys demonstrated a widespread recognition of excess sag problems within the electric transmission industry and identified the criteria for the SLiM device.
- Employing feedback from the utility industry and a number of design iterations, the investigators explored a wide variety of devices and configurations for the SLiM device before finally arriving at a robust design.
- In-house testing, backed up by close correspondence with several shape memory alloy manufacturers and a search of the current literature, led to the most appropriate alloy selection for the current SLiM design.
- A swaging technique for holding the shape memory alloy wires, without having to thread or otherwise machine the alloy, was developed and validated. Because shape memory alloys are difficult to machine and almost impossible to weld to a dissimilar metal, this was one of the major challenges in the SLiM design.
- We designed, constructed, and used custom load frames with continuous data acquisition as tools to investigate the behavior of sag mitigating devices, and to measure performance characteristics of the final design and its components.
- Live-line tests successfully demonstrated the functionality of the SLiM device.
- Reliability testing demonstrated that the device has good fatigue behavior, corrosion resistance, and integrity, and that the resistance across electrical connections within the device will not increase during its service life.
- As an offshoot of a SLiM design iteration, we developed the SmartConductor and successfully tested it on a live line.
- We developed a software technique (complex terrain modeler) to optimize the number and location of SLiM devices necessary to mitigate sag on a given section of transmission line.

5.0 Conclusions and Recommendations

The goal of the SLiM project was to create a simple, robust, affordable, compact, and passive control device that could be easily installed on a span to resolve sag problems or to permit up-rating of the line. Our objectives were achieved through a combination of research efforts, feedback from the utility industry, cooperation with materials manufacturers, and an iterative design / testing procedure.

The final SLiM design was the first of its kind to effectively reduce conductor sag in a live-line demonstration. Moreover, we also developed and proved the SmartConductor on a live-line test. Although the range of motion of the SmartConductor is less than that for the SLiM device, its off-the-shelf design provides a lower-cost alternative for applications with less severe sag issues.

SLiM and SmartConductor devices can eliminate the thermal sag problem faced by many utilities in the world. Since the production and installation of these devices are simple, it will become a very attractive alternative to other sag mitigation techniques. Based on a simple market analysis, considering conservative market size and market penetrations, we estimate the demand for this product will be in excess of 30,000 units in North America alone.

Recommendations

Before the SLiM device can be adopted by the utility industry, some additional tasks are needed. These include development of a production prototype to optimize the cost of making the devices and a utility-wide demonstration of the device on actual transmission lines. Furthermore, we feel a relationship with an existing major manufacturer, supplier, and / or distributor in this industry will benefit the production and introduction of this device. Other plans include publishing articles and making presentations at various forums to increase the awareness about this product.

Work on the design of the production model has already started and we are exploring partnerships for finalizing manufacturing processes, distribution, and sale / support of these devices. Also, in cooperation with Electric Power Research Institute (EPRI), a tailored collaboration project is being developed where production versions of the device will be installed on actual transmission lines and their performance monitored for approximately one year. We are also preparing a number of presentations about this device to be given in IEEE and other forums.

With a production plan (see Appendix T) and the proposed large-scale demonstration project by the EPRI in the works, we are confident that the SLiM and SmartConductor devices will have a strong and promising future in the electric transmission industry.

Benefits to California

The Slim and SmartConductor devices have the potential to offer the following benefits to California.

- Improved reliability and quality of California's electricity system by reducing the risk of brownouts (the curtailment of electric deliveries due to line constraints) and power supply interruptions;

- Improved safety of California's electricity by significantly reducing the risk of electrocution and fires caused by sagging transmission and distribution lines; and
- Reduced environmental and public health risks / costs of California's electricity system by avoiding the need to build additional transmission towers.

References

1. *California Transmission Line Ownership*, California Energy Commission Web site, July 2002.

2. "Quarterly Fuel and Energy Report," California Energy Commission, September 2002.

3. *California Statewide Weighted Average Retail Electricity Prices*, California Energy Commission Web site, July 2002.

4. *EMTP Users Guide*, Version 3.1, Electric Power Research Institute; analysis conducted at IREQ.

Appendices

Appendices contain proprietary information and are not included in the main body of this report. For more information regarding the appendices, contact the contractor at the address below.

Appendix A	Market Survey of Sagging Line Issues in the Utility Industry 2.6-1
Appendix B	Survey of Existing Power Grid 2.1-1
Appendix C	Criteria and Targets 2.1-(2-5)
Appendix D	Summary of Designs 2.2-1
Appendix E	Line and Insulator Contact Methods 2.2-2
Appendix F	Actuator Heating Methods 2.2-3
Appendix G	Design and Testing of the SLiM and SmartConductor Prototypes 2.10-1
Appendix H	Electric Field and Corona Behavior 2.2-4
Appendix I	Impact of SLiM on the Transient Behavior of a Transmission Line 2.2-5
Appendix J	Effect of SLiM on the Vibration Characteristics of a Transmission Line 2.2-7
Appendix K	Laboratory Test Results for Small-Scale SLiM Prototype 2.8-1
Appendix L	Shape Memory Alloy Selection for the SLiM Prototype Actuator 2.8-2
Appendix M	SLiM Laboratory Prototype Testing 2.5-1
Appendix N	Full Scale Lab Testing Results 2.8-3
Appendix O	Field Testing Plan for the Functionality of the SLiM Device 2.7-1
Appendix P	Summary Report for SLiM and SmartConductor Functionality Testing 2.10-2
Appendix Q	Reliability Testing of the SLiM Prototype 2.10-3
Appendix R	Development of a Complex Terrain Modeler 2.2-6
Appendix S	Simulation of the Effect of SLiM on Line Sagging 2.2-8
Appendix T	SLiM & SmartConductor Production Readiness Plan 2.11-1

Manuchehr Shirmohamadi
Principal Investigator, President
Material Integrity Solutions, Inc.
3254 Adeline St., Suite 200
Berkeley, CA 94703